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STATE-OF-THE-ART FOR ASSESSING EARTHQUAKE HAZARDS IN THE UNITED STATES.

Report 19,

THE EVIDENCE FOR RESERVOIR-INDUCED MACROEARTHQUAKES

by

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The published evidence of reservoir-induced macroearthquakes is critically reviewed. The evidence is partitioned into three types: (a) evidence of a postimpoundment increase in seismicity, (b) correlation evidence that is composed of a plot of a reservoir variable and a seismicity variable and, in most cases, an auxiliary variable, time, and (c) evidence based on the slope of the magnitude-frequency relationship (b value evidence).

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The basic source for each of these types of evidence is a suitably edited catalog of earthquake occurrences. Recommendations are given regarding catalog preparation and editing.

The types of evidence are examined to recognize the effects of common methods of data acquisition and treatment. Postimpoundment change in seismicity can be assessed using certain recommended statistical tests. Recommendations are made regarding construction and interpretation of correlation evidence. The interpretation of correlation evidence is subjective because the assumptions required to construct and interpret the evidence cannot be verified. Evidence based on the b value is shown to be useless as a discriminant to identify induced seismicity from normal seismicity.

Eight cases of reservoir induced macroearthquakes are reviewed. These eight cases are: (a) Hoover/Lake Mead, (b) Kariba, (c) Kremasta, (d) Koyna, (e) Kurobe, (f) Manic 3, (g) Hsinfengkiang, and (h) Nurek. Three cases (Hoover, Manic 3, and Nurek) appear to be well documented cases of induced seismicity. Two cases (Kurobe and Kremasta) are located in seismically active areas and the seismicity attributed to the reservoir is consistent with the natural local seismicity. These two cases do not appear to be cases of induced seismicity. The three remaining cases (Hsinfengkiang, Kariba, and Koyna) present insufficient information to support a conclusion.

PREFACE

This report is part of ongoing work at the U. S. Army Engineer Waterways Experiment Station (WES) under CWIS 31039, "Seismic Effects of Reservoir Loading and Fluid Injection in Wells," sponsored by the Office, Chief of Engineers, U. S. Army.

The report was prepared by Dr. R. B. Meade under the direction of Dr. E. L. Krinitzsky, Engineering Geology and Rock Mechanics Division (EG&RMD), Geotechnical Laboratory (GL). General direction was provided by Dr. D. C. Banks, Chief, EG&RMD, Mr. C. L. McAnear, Acting Chief, GL, and Dr. W. F. Marcuson III, Chief, GL. This report was reviewed by Mr. S. J. Johnson, Consulting Engineer, Vicksburg, Miss., and Mr. W. R. Judd of Purdue University, West Lafayette, Ind., to whom the author is grateful for many helpful suggestions.

Permission was obtained to reproduce certain tables and figures. The appropriate credit is indicated on those tables and figures.

COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE, were Commanders and Directors of WES during the period of this study and the preparation of this report. Mr. Fred R. Brown was Technical Director.

A

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement may be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acre-feet	1233.489	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
miles (U. S. statute)	1.609347	kilometres
square miles	2.589998	square kilometres
tons (force)	8896.444	newtons

STATE-OF-THE-ART FOR ASSESSING EARTHQUAKE HAZARDS IN THE UNITED STATES

THE EVIDENCE FOR RESERVOIR-INDUCED MACROEARTHQUAKES

PART I: INTRODUCTION

Purpose

1. This report is a critical examination of the published reports of reservoir-induced macroseismicity. These reports will be examined in terms of the supporting evidence. Specifically, the inferential power of the evidence will be examined to determine its limits of applicability and to describe the appropriate use of such evidence. Recommendations will be made concerning appropriate statistical use of existing seismicity data and the type of information that should be collected.

Background

2. During the late 1930's, earthquake activity in the vicinity of Lake Mead caused local concern. Carder (1945) reported on this activity and produced evidence correlating the release of seismic energy with water load. The epicenters were clustered near the dam and the largest of these earthquakes was about magnitude 5. In the 1960's, earthquakes occurred near the site of several large reservoirs. At Kariba, Zambia, seismic activity occurred within the reservoir. This region was supposedly aseismic prior to the impoundment of Kariba. The largest earthquake near the reservoir was about magnitude 5.8. At Kremasta, Greece, no large earthquakes were reported within 40 km of the damsite for the 15 years preceding impoundment. After impoundment, thousands of earthquakes were reported in the area, the largest of which was about magnitude 6.2. At Koyna, India, the region of the reservoir was considered aseismic despite the occurrence of several severe earthquakes felt in

nearby coastal areas. After impoundment of the reservoir, felt* earthquakes, the largest of which was about magnitude 6.5, occurred at locations within 25 km of the dam. In all of these cases, the apparent increase in seismic activity subsequent to reservoir impoundment suggests that the reservoir triggered the earthquakes.

3. The National Academy of Sciences (1972) published a report entitled "Earthquakes Related to Reservoir Filling." The report contained three sections. First, recommendations were given regarding collection of geologic, geodetic, and seismological information at reservoir sites. Second, case histories were drawn from published accounts of reservoir-associated seismicity. Third, the possible mechanisms of reservoir-induced earthquakes were discussed. The report called for increased study of the phenomena. The ultimate goal was determination of "acceptable risk" regarding induced seismicity.

4. In 1974 (Judd 1974) and again in 1976 (Milne 1976), the journal Engineering Geology devoted an issue to the topic of induced seismicity. These two special issues provided a wide variety of case histories and state-of-the-art commentary on possible triggering mechanisms.

5. In 1976, Elsevier publishing house released the book Dams and Earthquakes by Gupta and Rastogi (1976). The authors presented a very complete study of the subject, drawing from published case histories. The authors presented their interpretation of the characteristics of reservoir-induced seismicity (RIS).

6. In 1977, a study of reservoir-induced seismicity was conducted as a part of earthquake evaluation studies for Auburn Dam. The report was authored by Woodward-Clyde Consultants under contract to the Bureau of Reclamation. The purpose of the report was to compare the reservoir proposed at Auburn Dam, Calif., to those reservoirs that have produced induced seismicity. Fifty-five reservoir cases were reviewed. Sixteen were classed as accepted cases of induced seismicity, thirty-five as questionable cases, and four at which the seismicity was not induced.

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* The term "felt" when used to describe earthquake intensity means that local inhabitants have identified the earthquake occurrence from the sensations caused by the earthquake.

7. In 1979, Woodward-Clyde prepared a report for the U. S. Geologic Survey (USGS) that was published as Open File Report 80-1092 (Packer et al. 1979). This report extended the work performed during the Auburn Dam studies. Sixty-four reservoir cases were reviewed and classified as accepted cases of RIS, questionable, or not RIS. This total included the fifty-five cases classified in the 1977 report. The 1979 results differed from the 1977 results substantially because the criteria used to classify the cases in 1979 differed from the 1977 criteria. These criteria will be discussed in a later section.

Types of Evidence

8. Reservoir-induced seismicity is the occurrence of earthquakes that are triggered by the operation of the reservoir. A triggered earthquake has no unique features that can be used to identify it from a naturally occurring event. The lack of diagnostic features in an induced event is a major obstacle to identifying cases of induced seismicity.

9. In the Auburn Dam studies Woodward-Clyde Consultants categorized cases of alleged induced seismicity into accepted cases, questionable cases, and unrelated cases. Accepted cases of induced seismicity have postimpoundment earthquakes that are temporally and spatially related to the reservoir. Accepted cases include sites which had little or no seismicity prior to impoundment, sites where the earthquakes show good temporal correlation with reservoir operations, and sites where the earthquakes had good spatial correlation with the reservoir.

10. Questionable cases had insufficient information to permit a judgment to be made concerning temporal and spatial correlation of the seismicity with the reservoir. Unrelated cases had either no increase in seismicity after impoundment or no temporal or spatial relationship between the reservoir and the observed seismicity.

11. The issue of sufficiency of the information is not formally addressed in the Auburn Dam studies. Comments were made concerning data

reliability but no criteria are suggested to judge data quality.

12. In the 1979 study done for USGS, Woodward-Clyde Consultants used a circular area centered on the reservoir having a radius equal to the greatest dimension of the reservoir to be the reservoir "local area." Macroseismicity was evaluated independently of microseismicity. As in the earlier study the spatial and temporal relationship between the reservoir and the seismicity was assessed. Any seismicity occurring within the local area after impoundment was assumed to be reservoir-induced. Many of the reservoir cases classified as questionable in the 1977 study were classified as accepted cases using the 1979 criteria.

13. Gupta and Rastogi (1976) state that collectively reservoir-induced earthquakes have characteristics that set them apart from normal earthquakes. The characteristics are seen from (a) the magnitude-frequency relationship, (b) the relationship of the magnitude of the main shock and the largest aftershock, (c) the time distribution of the foreshocks and aftershocks, and (d) the foreshock-aftershock pattern.

14. The parameter used to show characteristics (a) and (d) is the slope of the magnitude-frequency relationship commonly called the b value. Specifically, the foreshock b value is higher than the after-shock b value, and both foreshock and aftershock b values are higher than regional b values and b values for normal aftershock sequences.

15. Reports of induced seismicity have come from many different authors. The kinds of evidence most commonly used can be partitioned into three types of evidence. They are presented in decreasing order of their importance:

a. Postimpoundment increase in seismicity.

b. Correlation of water level (or similar reservoir parameter) and seismic activity.

c. Display of a distinctive aftershock pattern as expressed by an unusually high slope of the magnitude-frequency relationship. Throughout this report this type of evidence is called b value evidence.

16. The first two types of evidence (a and b) are generally presented in such a way that they stand on their own merits. Examples are Carder (1945), Gough and Gough (1970a), and Hagiwara and Ohtake (1972).

Type c evidence is usually presented with support of either type a or type b evidence. Examples are Gupta, Rastogi, and Narain (1972), Leblanc and Anglin (1978), and Rogers and Lee (1976). If all three types of information were available and applied to a reservoir, the case would be placed into one of 18 categories as shown in Figure 1. The most convincing case of induced seismicity is where a postimpoundment increase

TYPE OF EVIDENCE	CATEGORY
I POSTIMPOUNDMENT CHANGE IN SEISMICITY	I INCREASE N NO CHANGE D DECREASE
II CORRELATION OF WATER LEVEL AND SEISMICITY	+ POSITIVE 0 NO CORRELATION - NEGATIVE
III b VALUE COMPARISON WITH REGIONAL VALUES	T TYPICAL U UNTYPICAL

MOST CONVINCING CASE OF INDUCED SEISMICITY I+U

MOST CONVINCING CASE OF INDUCED ASEISMICITY D-U , D-T

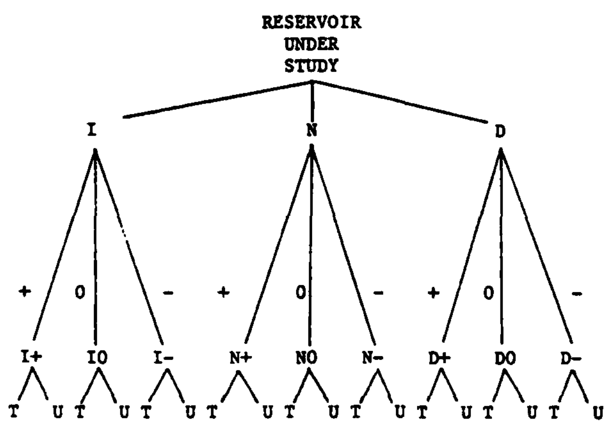

Figure 1. Credibility diagram

in seismicity is indicated and the seismic activity correlates strongly with fluctuations in the reservoir level and the aftershocks associated with the reservoir display an unusually high b value. This is indicated in Figure 1 as category I + U. Although reservoir-induced aseismicity is not frequently asserted, it is possible. The most convincing evidence of induced aseismicity would fall into categories D - U or D O T.

The implication of the b value is unknown in cases of reduced seismicity. As stated previously, the most convincing evidence places a reservoir in category I + U. Other possible categories for cases of induced seismicity are I + T, I O U, N + U, and N + T. All other categories present no evidence of induced seismicity or present conflicting evidence. If no information is available, no inference is justified. When a lack of a particular type of evidence makes it improper to assign a category, the case will be considered questionable and a default label of Q will be assigned for that type of evidence.

Induced Seismicity

17. Less than 1 percent of the world's reservoirs have been associated with macroearthquakes (Richter magnitude greater than 3) (Stuart-Alexander and Mark 1976). This percentage increases as small and shallow reservoirs are culled from the data base. The percentage grows to 14 if only reservoirs that are deeper than 95 m are considered. Despite the low incidence of induced seismicity, consideration of this phenomenon has had a significant impact on the authorization of new reservoir projects and the seismic hazard evaluation of existing projects. The response to the vague threats posed by induced seismicity is to increase the conservatism in seismic design. The monetary cost of this increased conservatism is high and it becomes important to determine if the threat of induced seismicity is real or imagined. The evidence available to evaluate induced seismicity is circumstantial. Despite numerous claims to the contrary, no proof of induced seismicity exists. Alternative explanations always are possible. The evidence is conclusive only in terms of subjective judgment. Based on his appraisal of the evidence the researcher forms a judgment concerning the occurrence of induced seismicity. The judgment is published and repeated in citations by others. It is these subjective judgments which collectively form the hazard of induced seismicity. To determine the degree of conservatism appropriate for seismic design, the designer must form his own judgment based on the evidence or be prepared to accept the judgment of others.

18. The hazard of induced seismicity is formed in large measure from judgments concerning cases of induced macroearthquakes. Most macroseismicity is generated by tectonic forces. Microseismicity can be generated by tectonic forces or it can be generated by nontectonic forces. Potential nontectonic sources of microearthquakes include gravity slumping, thermal forces, cavity collapse, mining, detonation of explosives, and surface loadings such as reservoirs. Reservoir-induced microearthquakes might be related to tectonism or they might represent nontectonic seismic activity. Reservoir-induced macroearthquakes represent a release of tectonic forces.

19. Eight of the most widely accepted cases of induced macroearthquakes have been selected for review. The eight cases include the only four instances in which damaging earthquakes were associated with reservoir impoundment. A summary of reservoir depth and volume and the size of the largest local earthquake is shown in Table 1. These cases will be examined using the data presented in the literature.

Table 1

Selected Cases of Induced Macroearthquakes

Reservoir	Location	Depth, m	Volume $\times 10^6$, m^3	Largest Earthquake*
Hoover (Lake Mead)	U.S.A.	166	35,000	$M_L = 5.0$
Kariba	Zambia/ Rhodesia	122	175,000	$m_b = 5.8$
Kremasta	Greece	120	4,750	$M_s = 6.3$
Koyna	India	103	2,780	$M_s = 6.5$
Kurobe	Japan	186	149	$M_s = 4.9$
Manic 3	Canada	98	10,423	$m_b = 4.3$
Hsinfengkiang	China	80	10,500	$M_s = 6.1$
Nurek	U.S.S.R.	215	11,000	$M_s = 4.5$

* M_L indicates a local magnitude scale was used.
M_s indicates magnitude was measured from amplitude of surface waves.
m_b indicates magnitude was measured from amplitude of body waves.

20. The original evaluations usually have remained with each case. This reviewer will attempt to develop a standard methodology to evaluate the evidence. In the final outcome a judgment will be rendered based on the appraisal of the evidence plus consideration of alternative explanations. It is in the evaluation of the evidence that subjective judgment unavoidably occurs. Like all other judgments, the verdict in this report represents an opinion. However, the use of a system of data appraisal that evaluates the quality of the data and recognizes the limitations of the data will result in a reasonable judgment.

Circumstantial Evidence

Nature of the evidence

21. In experimental terms, the phenomenon of reservoir-associated seismicity has been observed in the field during full-scale experiments. Under field conditions, the factors which influence the experiment are seldom controlled and many may not be observable. Consequently, interpretation of the phenomenon is difficult. Theories are advanced to explain observable results, but proofs of such theories are impossible.

22. To prove a cause and effect relationship through an experiment, all factors must be known and preferably controlled. Those factors not controlled must at least be observed. The independent variables must be identified with respect to the dependent variables. Then an A-B-A form experiment must be performed. In situation A the variables believed to be the controlling causative factors are manipulated to provide a known set of conditions. The asserted dependent variables are observed and their behavior is quantified. Then the controlling factors are changed to a different set of conditions, situation B. The resultant changes in the dependent variables are recorded. Then the conditions corresponding to situation A are restored. Again the dependent variables are observed. If the dependent variables assume the same values each time situation A is imposed and change to a different value under situation B, then a causal relationship is proved. If not all factors are known and observable, a causal relationship cannot be proved.

23. In field situations rarely are all factors observable and often not all are even identified. This uncertainty forces the observer to explain his observations in some manner which is consistent with all known information. Any explanation which is consistent with all the known information must be considered as a possible explanation. Unfortunately, several possible explanations may exist. None of the possible explanations can be proved wrong since they are all consistent with all known information, nor can any be verified because all the uncertainty regarding the experiment cannot be removed.

24. Not all possible explanations have equal value. The value of an explanation lies in the way it deals with the uncertainty surrounding the experiment. One method for assessing the value is to associate the explanation with the occurrence of an unlikely or rare event. If the truth of an explanation requires that a very unlikely event has occurred, one has grounds for devaluing the explanation. This concept is the basis for hypothesis testing. Although some explanations may be devalued by hypothesis testing, there is no guarantee that this process will result in the elimination of all but the true explanation. An engineer or scientist cannot base a conclusion solely on a hypothesis test. The test does provide some information, but this information is never conclusive.

25. The types of evidence presented in the literature were cited earlier. Consider the following hypothetical case. Reservoir A has all three types of evidence, placing it in category I + U. However, another location called area B in the same region but remote from the reservoir also has experienced a recent increase in seismicity. The seismicity in area B can be correlated to rainfall and seasonal groundwater fluctuation. The seismicity occurring at site B also had a high b value. The proper conclusion may be that the region is experiencing a change in seismicity which is unrelated to the reservoir at site A. A decision regarding the existence of reservoir-induced seismicity requires subjective judgment. This requirement exists because the evidence is circumstantial.

<u>Statistics</u>

26. Statistics is a tool that permits the engineer to strengthen

inferences based on available data and reasonable assumptions. Certain requirements should be fulfilled before statistical techniques can be applied. These requirements will be discussed later. Statistical methods even if properly applied do not provide specific conclusive results because statistics cannot eliminate uncertainty. However, the results provide additional information concerning the likelihood of finding the observed data under certain assumed conditions. This information becomes part of the total volume of information to which the engineer can apply his judgment. Statistics can provide considerable insight if used wisely and conversely, can be misleading if improperly applied. With this in mind, the process of hypothesis testing will be examined.

27. The purpose of hypothesis testing is to quantify uncertainty. Hypothesis testing will be used as an aid in categorizing a given reservoir. The procedure is as follows: A statement is made concerning the phenomenon of interest. In this case this statement is based on the type of evidence. The statement must be phrased in statistical terms. The manner in which the hypothesis is phrased and the statistical test which then is performed are contingent on the assumptions made by the tester. Based on these assumptions, the researcher adopts a statistical model which permits the data (evidence) to be tested. The test answers the following question: "Assuming the hypothesis is true and assuming the statistical model is appropriate, what is the likelihood that the given data (evidence) could occur?" If the likelihood is sufficiently low, one has grounds for rejecting the hypothesis. The hypothesis being tested is labeled the null hypothesis. If the null hypothesis is rejected, one must accept an alternate hypothesis as true. Preferably, a researcher will set up his experiment and formulate his hypothesis prior to gathering data. However, the nature of this report required that an appropriate statistical test be performed on published data.

PART II: SEISMICITY

28. The assessment of seismicity is basic to the examination of induced seismicity. The first type of evidence is a comparison of preimpoundment seismicity with postimpoundment seismicity. Correlation evidence pairs a reservoir variable with a seismic variable. The determination of the b value requires detailed seismic information. The collection and preparation of basic seismic data will be discussed in detail.

Definition of Seismicity

29. A common factor in all three types of evidence is the measurement of seismicity. It is important that a precise definition be made. In this paper, seismicity refers to the occurrence of earthquakes. To fully describe the occurrence requires five variables. One variable describes size (M) in terms of energy. A magnitude scale will be most often used for this variable. One variable describes the time (t) of occurrence. Three variables (x, y, z) are required to describe the location of the occurrence. Each earthquake can be fully described by the following notion:

Earthquake Occurrence = E (size, time, location)

E (M; t; x, y, z) is the form which will be used throughout this paper. An example is a fictitious earthquake which occurred near Denver, Colo., on 10 April 1966. Its description is E (4.7; 10 April 1967, 14:00; lat. 39.8N, long. 104.9W, 1750 m, msl).* Often an incomplete description is given because focal depth is not determined. Earthquake catalogs usually provide no focal depths. In that case the description is E (M; t; x, y; -). The dash represents undetermined focal depth. Earthquakes have other attributes such as duration and acceleration-time history but these do not describe the occurrence (birth) of the earthquake.

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* Mean sea level (msl).

Seismic activity is described by the collection of earthquake occurrences as defined by all five variables. The limitations on those five variables define the detection level, which will be examined in detail in a later section. At this point, it is sufficient to note that the completeness of the description (the detection level) has a profound effect on the inferential power of the seismicity data.

30. There are two common quantitative concepts of seismicity. One is where regional seismicity is expressed by a magnitude-frequency relationship. The form usually used is $\log N = a - bM$ where N equals the number of earthquakes observed, M equals magnitude and a and b are constants for a particular set of observations. Several conventions exist for selecting which values constitute N and which magnitude scale (m_b, M_s) to use. A detailed summary of these practices can be found in Evernden (1970). A magnitude-frequency plot treats seismicity as a univariate parameter rather than as a five-variable parameter.

31. Another concept of seismicity uses the rate of earthquake occurrence as the measure of seismicity. The occurrence of a small magnitude event is given the same weight as the occurrence of a large magnitude event. In both these cases, magnitude-frequency and occurrence-frequency, the reduction in the dimension of seismicity from five variables to one variable entails discarding information to provide the convenience of a simple model. The consequences of assuming a simple model will be examined in a later section.

Detection Level

32. The definition of seismicity established earlier will also define detection level. The definition is $E\ (M;\ t;\ x,\ y,\ z)$, where M is a size variable, t is a time variable, and x, y, z are location variables. Detection level can be specified using set notation. Let the set of all earthquakes be E . The earthquakes which are detected comprise set D . The specifications which identify D from all E are loosely called the detection level. The same detection level should

be used to gather all data, but it seldom is. The accuracy of each type of specification can influence the statistical use of the data. There is no consensus on the specification of magnitude and the description of the accuracy of the location variable. The most common problems are summarized below:

a. Magnitude. The magnitude is a measure of the energy released by the earthquake. Several magnitude scales are commonly used. The magnitude can be measured using body wave (m_b), surface wave (M_s), or by some instrument correlation (M_L). Microearthquakes are frequently recorded on a scale based on the characteristics of the detection instruments. Earthquakes that occurred before the availability of seismic instrumentation are cataloged using an intensity or damage scale. To use the size variable in a statistical test, the same scale must be applied to all earthquakes. Some earthquakes may require conversion from one scale to another. The accuracy with which the scale is applied must also be considered. It is possible that apparent changes in the magnitude distribution may be due to changes in the accuracy of size determination.

b. Epicenter. The location of the source of earthquake energy release projected to the earth's surface is the epicenter. This location can be determined instrumentally with the accuracy of the determination dependent on several factors. The most important are the size of the event, the proximity of the epicenter to the instruments, and the detection on more than one device. The epicenters of historical earthquakes that occurred before availability of instruments can be estimated using intensity maps. The accuracy of this type of epicentral location may be on the order of tens of kilometres. If location data are to be used to sort the data, the limits of the location accuracy should be reported.

c. Focal depth. The focal depth is not generally available unless special instrumentation has been installed to gather these data. The focal depth when added to the epicenter provides a complete description of the location of the earthquake. Accuracy limitations on focal depth determination should also be reported.

33. The published data concerning seismicity are generally in the form E (M; t; x, y, -) when focal depths are generally not available. The time variable t is usually the most well established. The magnitude or size variable could be measured on one of several scales. For historical data an intensity (damage) scale is often used. For

microearthquakes, empirical correlations are frequently used to establish the size of very small events ($M < 0$). The most commonly used magnitude scales are based on body wave, surface wave, or some local criterion. Whatever scale is used should be uniformly applied. Uniformity of application extends to the level of accuracy.

34. For example, consider the data shown in Table 2. First, a

Table 2

Sample Seismicity Data

	Example	Magnitude
	14 Jan 32	4.0*
	31 Oct 32	4.0*
	23 Mar 35	4.0*
28 years	11 Jan 38	5.0
	15 Nov 38	4.2/5.0
	10 Mar 43	3.7
	12 May 48	3.8
	10 Nov 54	4.4
	Reservoir Filled 1959	
	5 Apr 59	3.6
	15 Sep 59	3.5
	6 Jun 62	5.2
20 years	26 Jun 67	3.5
	24 Jul 73	3.8
	24 Nov 73	3.5
	25 Mar 78	4.5

Note: All epicenters are located within 25 km of the dam. Apparent threshold for detection $M_L = 3.5$
* Cataloged as Modified Mercalli (MM)I-IV and converted to M_L.

decision must be made concerning the record of 15 November 1938. Assume for the moment 5.0 is adopted as the magnitude and the records of 15 November 1938 are counted as a single event. Notice the pre-1938 magnitude values. It may be that magnitudes were not determined as accurately prior to 1938 and that each record was rounded off to the nearest half magnitude so that each magnitude 4.0 represents an event whose true magnitude fell between 3.5 and 4.4. If this were the case and if the later records were accurate to a tenth of a magnitude, it may be improper to apply certain methods of analysis which rely on equal accuracy in assignment of magnitudes. In fact, the pre-1938 data were categorized in terms of intensity and converted to magnitude.

35. The location variables x and y are often in terms of latitude and longitude. Their accuracy as in the case of magnitude may change with improved instrumentation and more accurate velocities. The error in location occasionally is recognized but rarely accounted for. The focal depth variable z is usually in kilometres or miles. Typically, the focal depth is not accurately determined. The focal depth must be determined from multiple instrument recordings located close to the epicenter. Ideally, focal depth should be determined by instruments located within one focal depth of the epicenter. Because of the necessity to have close-in detection to determine focal depths the error in determining focal depth is quite location-dependent. The limitation on the accuracy of the published data should be addressed in considering a hypothesis test. If a program is established to gather data, the selection of variable scales and the numbers and location of detection devices can be determined by the level of accuracy required in the analysis. The limits of accuracy can be translated into costs and a decision can be made regarding cost/benefit ratio or some other economic criteria.

Catalog Information

36. The employment of any of the three types of evidence necessitates making a catalog of earthquakes for the reservoir area. The limits of the area to be considered must be defined. Ideally, the area should include that portion of the earth's surface that caps the volume of the crust which is influenced by the reservoir. Within this volume of crust the load and fluid pressure of the reservoir could alter the stress or strength of the rock. To determine the dimensions of the influence area analytically requires a theoretical model which can predict how the

effects of the reservoir are distributed in the crust. Alternatively, the size of the influence area may be estimated empirically from the established cases of induced seismicity drawn from certain fluid injection case histories. Both the theoretical and empirical approaches will be discussed.

Theoretical estimates

37. A theoretical estimate requires use of a model to act as the prototype of the crust. Several models are available but the two most common are linear elastic models. In one case, elastic deformations are estimated based on a single phase media. In the other case, a consolidation model is used. The models require that the media be continuous. In the single phase model the media must be linear, elastic, isotropic, and homogeneous to obtain closed-form solutions. Although anisotropy and nonhomogeneity can be accommodated in principle, the solutions are formidable. More important, the distribution of stress and strain is very sensitive to the assumptions regarding anisotropy and conditions describing nonhomogeneity, as seen in Figure 2. Despite these problems, elastic theory has been used to estimate settlements due to the weight of the reservoir load.

38. Settlements at Lake Mead were predicted by Westergaard and Adkins (1934), using a two-layer model. Elastic compression was calculated in the upper crust that was estimated to be 29 km thick. Below this layer quasi-isostatic displacement, due to fluid flow in the lower layer and bending of the upper layer, was predicted. Raphael (1954) used level survey data to compare their theoretical displacements with the observed settlements and found that the displacements calculated for the elastic upper crust were within an order of magnitude of the observed settlements. The reservoir loads were assumed to be uniformly distributed over a set of six squares, 11.6 miles* on a side.

39. Gough and Gough (1970a) used a similar analysis to predict settlements at Kariba. However, they used a computer to perform the

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 7.

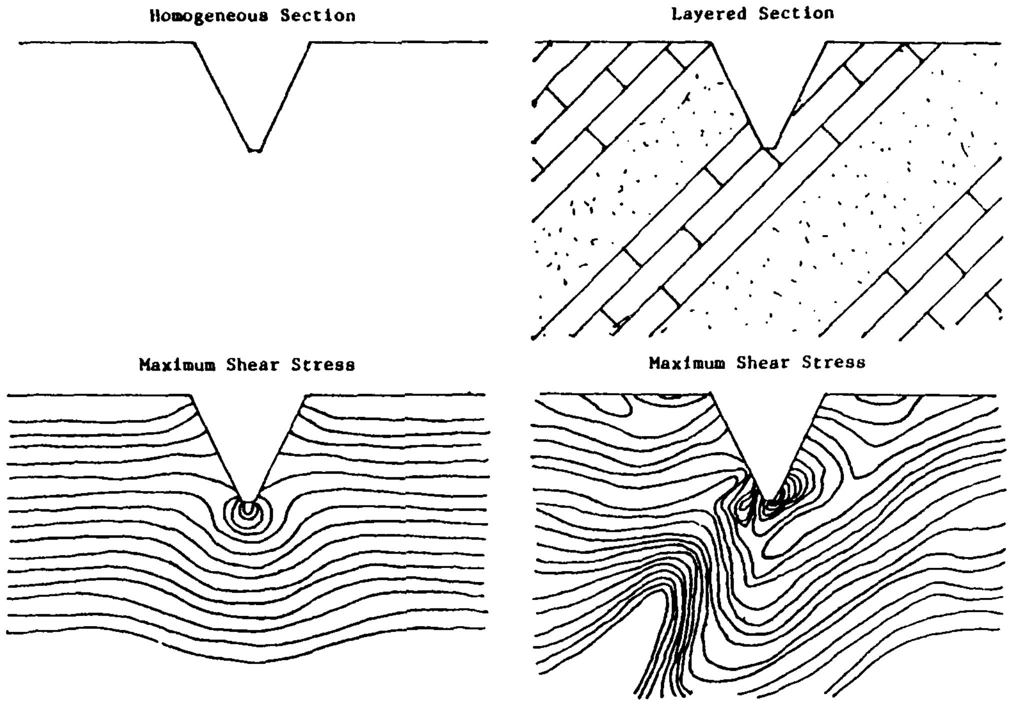


Figure 2. Shear stress distribution in homogeneous and layered sections (after Goodman (1965))

iterations required and consequently were able to approximate much more accurately the reservoir loading than was done in the case of Lake Mead. The values of the elastic constants were different from those used by Westergaard and Adkins. They checked their prediction with long level lines and found their results in excellent agreement with observed settlement.

40. More recently, Beck (1976) made a prediction for Oroville using a similar technique and the same values for the elastic constants as Gough and Gough. Lee (1972) predicted settlements at Lake Gordon, Tasmania, using elastic theory. No detailed comparisons with observed values of settlement have been made for the cases of Oroville and Lake Gordon. Wang et al. (1975) used the Boussinesq approach to calculate stress and displacement at Hsinfengkiang. No field measurements verifying the estimates are reported.

41. Using elastic theory, it is assumed that Hooke's law applies. Stress is proportional to strain and so the maximum induced stress should occur at the point of maximum strain. In all cases using a homogeneous model, the maximum displacement and therefore the maximum induced stresses occur beneath the reservoir and diminish with distance from the reservoir.

42. If the strength and residual stresses were uniform, failure in the form of earthquakes is predicted by a single-phase (dry) model at the location of the maximum induced shear stress, which is somewhere beneath the reservoir. The location of epicenters in cases of induced seismicity are often outside the reservoir boundary. In the cases of Lake Mead and Kariba, the epicenters do not cluster near the location of maximum settlements, considering both the theoretical and observed settlements. The location of the predicted maximum settlements is independent of the values of the elastic parameters, although the magnitude of the predicted displacements is controlled by the choice of the value of the elastic parameters. An assortment of values has been used. These values are listed in Table 3.

43. Unless the model can accommodate variations in the elastic parameters, the predicted maximum displacements and induced stresses will always fall within the reservoir boundary. The deflections predicted by Gough and Gough at Kariba are as shown in Figure 3. The deflections at Kariba were checked by running long level lines before and after impoundment. The line checked ran from Kariba to Makuti, a distance of about 55 km. The orginal leveling was done prior to impoundment and only the Kariba-Makuti line has been releveled and the results published. The agreement between the measured and calculated deflections are shown in Figure 4. The agreement is good and Gough and Gough conclude that (a) the deflection is elastic, (b) the assumed value of Young's modulus (0.85 megabars) is representative, and (c) the calculated vertical deflections for the region (shown in Figure 4) are valid.

Lake Mead level lines

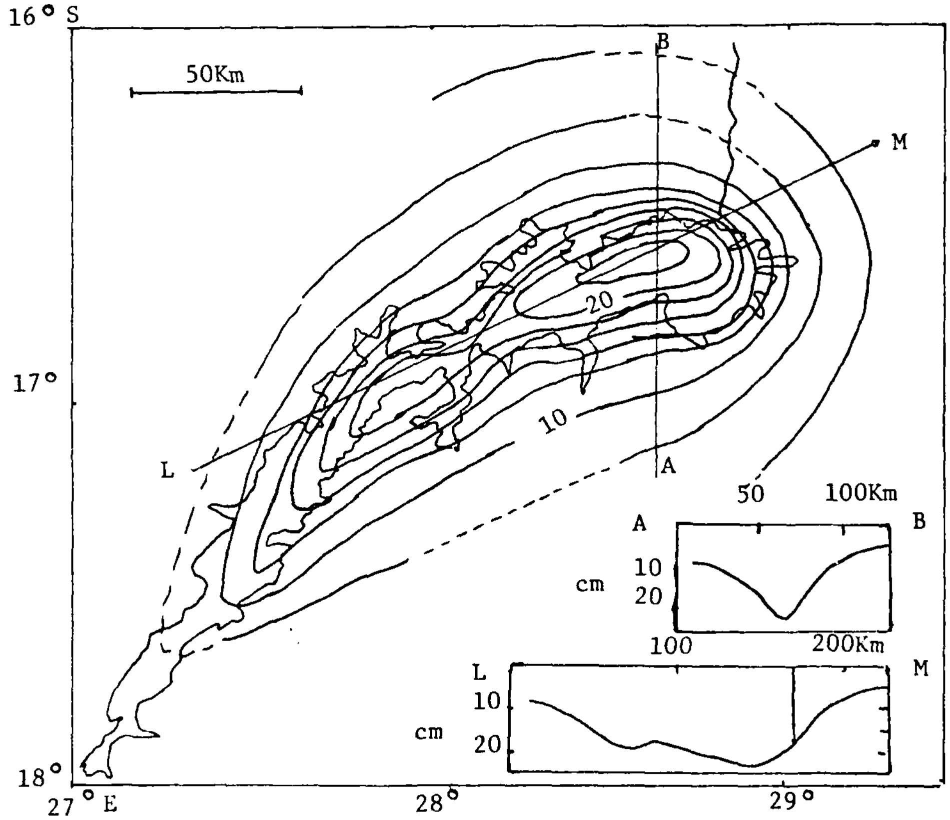
44. The most complete record comes from Hoover Dam. At the time of its impoundments Lake Mead was the largest reservoir in the world.

Table 3

Theoretical Models

Author(s)	Stress/ Strain	Fluid	Stability Criteria	Model Type	Stiffness/Modulus	Time Factor/ Permeability/ Coupling	Remarks
Westergaard and Adkins (1934)	X	N	None	EC and Isostasy	E = 390 kbars μ = 0.2 3-D	None	(1934) Lake Mead - accuracy checked by *Raphael* (1954)
Gough and Gough (1970a)	X	N	None	EC	E = 850 kbars μ = 0.25 3-D	None	(1970) Kariba - accuracy checked by authors
Snow (1972)	X	Y	Assumes fault type + M-C	DE	E = 350 kbars μ = 0.3 C ≅ 45 bars/cm Incompressible fluid 2-D plane strain	Imposed as transient-ultimate phases; no estimation of duration of transient *phase*	(1972) Infinite reservoir - discrete units of impermeable blocks and fluid filled fractures - fracture stiffness ≅ C
Lee (1972)	X	N	None	EC	"Rigidity" = 6.3×10^{11} dynes/cm^2 μ = 0.25 3-D ? E = 1550 kbars	None	(1972) Lake Gordon, Tasmania; unchecked estimate
Wang et al. (1976)	X	N	None	EC	E = 4.9×10^{11} dynes/cm^2 E = 480 kbars μ = 0.28	None	(1976) Hsinfengkiang; unchecked
Beck (1976)	X	N	None	EC	E = 850 kbars μ = 0.25 3-D	None	(1976) Oroville - selected points checked
Bell and Nur (1978)	X	Y	Assumes fault type and orientation, α	EC; two-phase varying permeability	G = 150 kbars E ≃ 390 kbars μ = 0.3; μ = 0.2 2-D	K_1/K_2 ε 10^{-2},1,10^2 Coupling = 0.6 K/K = 1 K = 2md	(1978) Oroville - unchecked complex model, see reference
Withers and Nyland (1978)	X	Y	Assumes fault type + M-C	EC; two phase	E = 850 kbars μ = 0.27 2-D	K = 2 millidarcy Coupling = 0.25	(1978) Kariba - unchecked because 2-D

NOTES: Range of E = 350 kbars to 850 kbars; μ = 0.2 to 0.3; μ = Poisson's ratio; X = stresses and strains predicted; Y = 2 phase model; N = single-phase (solid) model; M-C = Mohr-Coulomb Criteria; EC = Elastic Continuum; DE = Discretized Elastic Units



Contour Interval 2 cm

Figure 3. Computed settlement contours at Lake Kariba (after Gough and Gough (1970a))

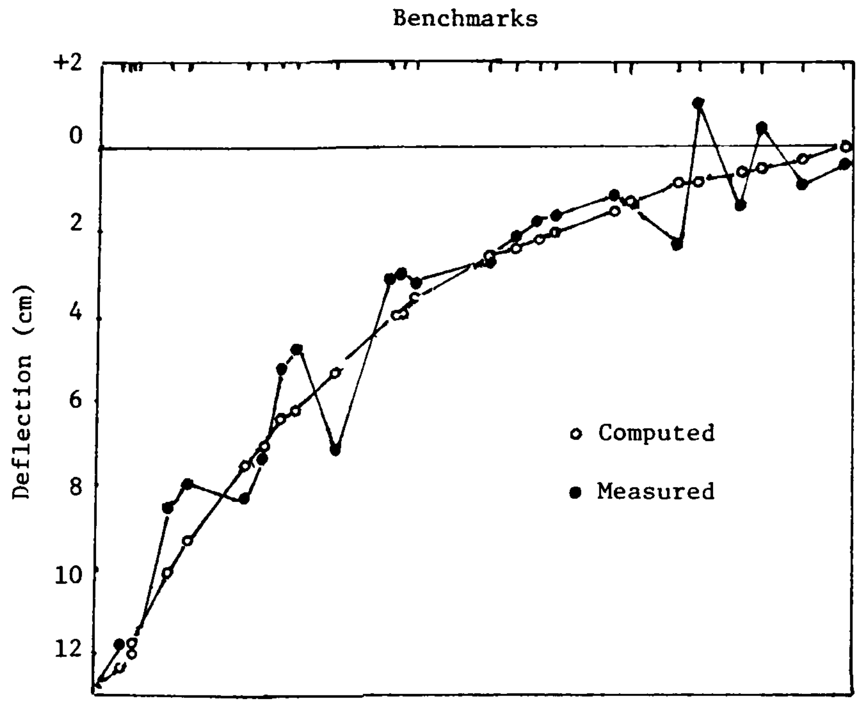


Figure 4. Settlement profile from Kariba to Makuti, 1968
(after Gough and Gough (1970a))

The settlement contours predicted by Westergaard and Adkins (1934) are shown in Figure 5. Level lines were run on routes shown in Figure 6. These lines were first run in 1935 coincident with impoundment. The lines were rerun in 1940-41, 1949-50, and 1963. The survey results provide a test of the assumption that the crust behaves elastically as a homogeneous body.

45. If the deflection pattern is similar to that predicted, then there is justification for using elastic theory to predict stresses. If the deflection pattern is not similar, then several possibilities exist. First, the crust may not behave elastically. Second, the crust may be elastic but the crust may have variable elastic parameters. Third, tectonic forces may be actively changing, which results in substantial regional strains. Fourth, the crust may act as a two-phase media (a porous solid saturated by a fluid). Any or all of these situations may cause the computed deflection pattern not to resemble the measured

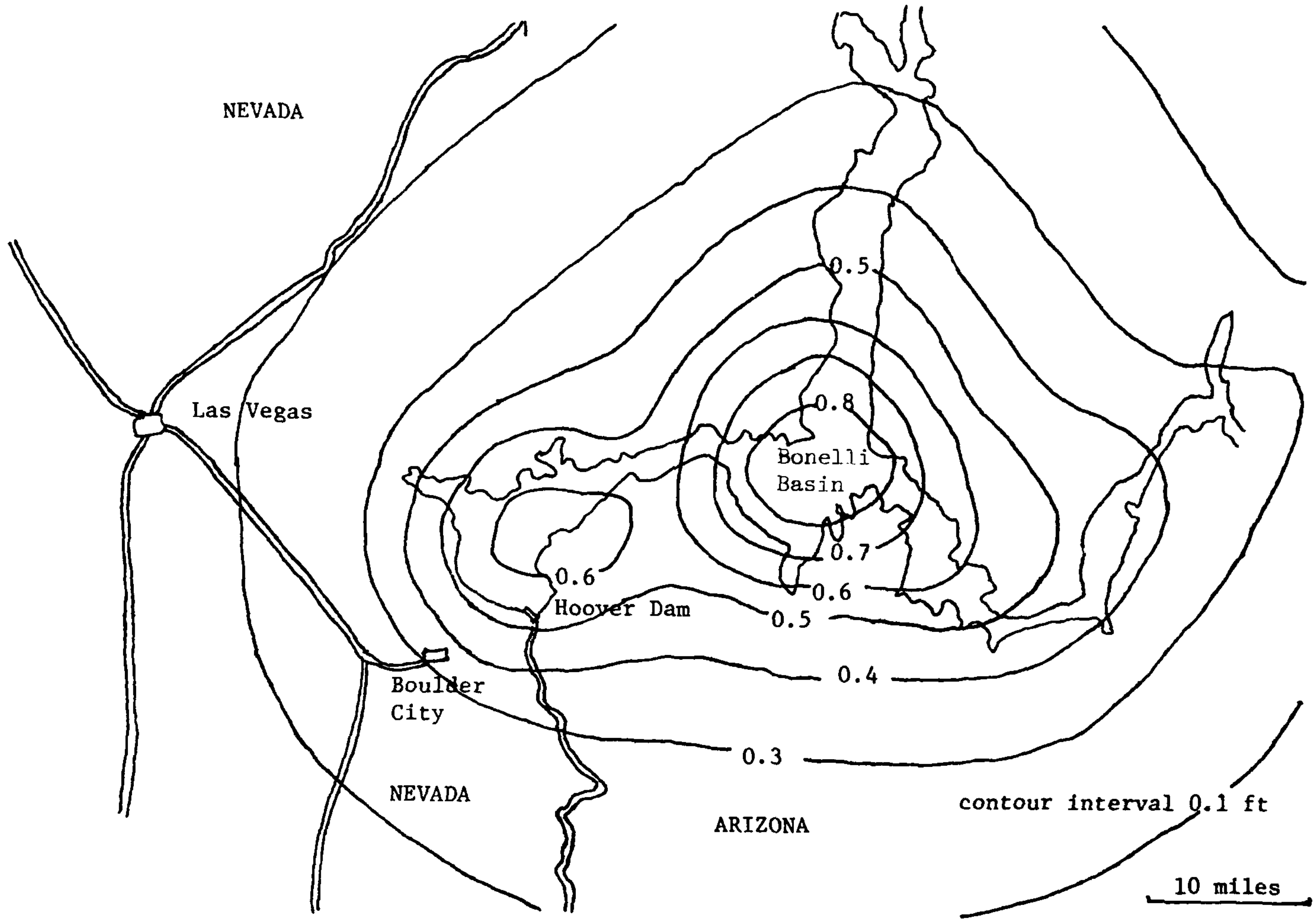


Figure 5. Computed settlement contours at Lake Mead (after Westergaard and Adkins (1934))

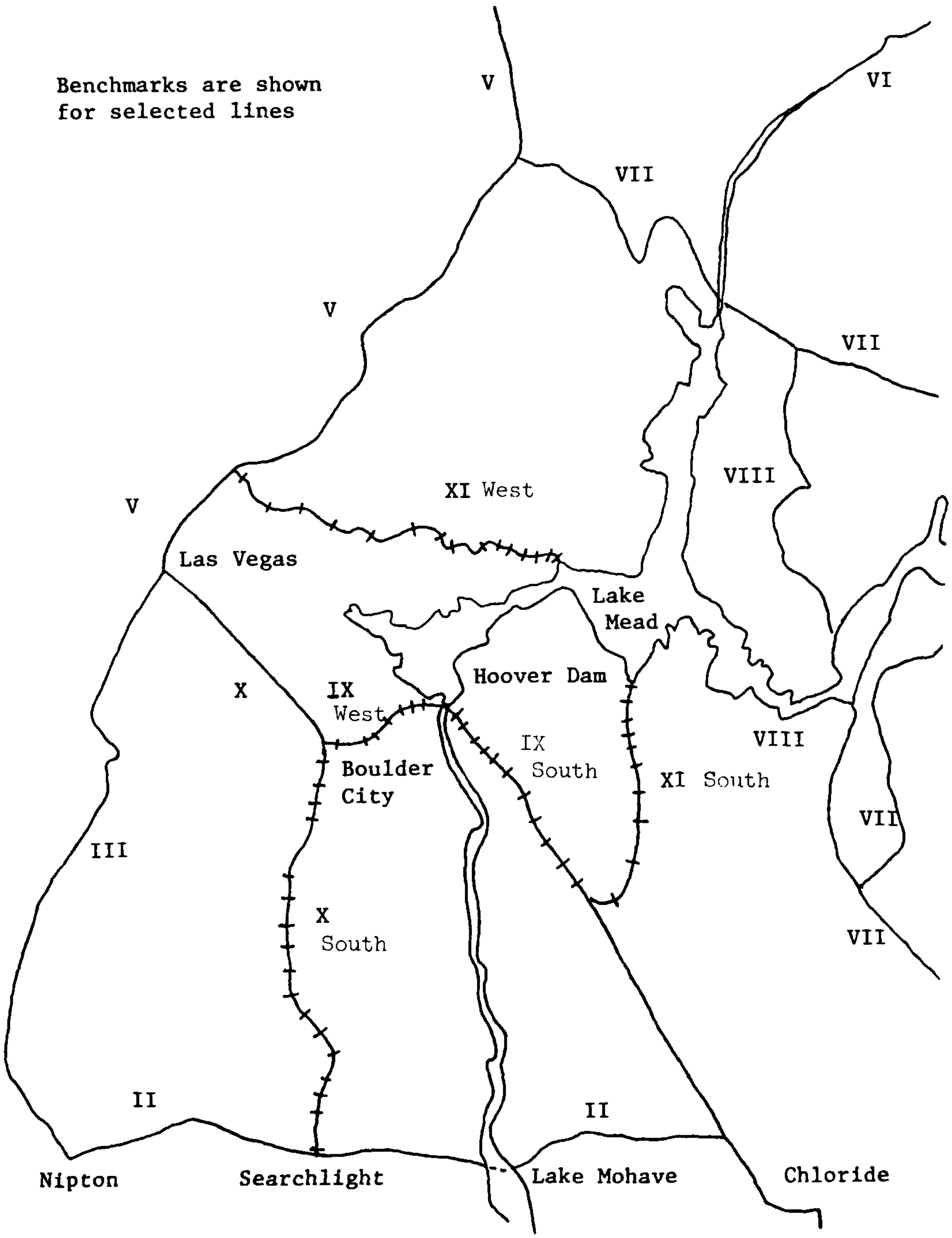


Figure 6. Level lines at Lake Mead (adapted from Lara and Sanders (1970))

deflection pattern. The deflection pattern in homogeneous elastic solids is independent of modulus but does depend on Poisson's ratio.

46. The first level survey was completed in 1941. These settlement contours are shown in Figure 7. The area of maximum deflection is

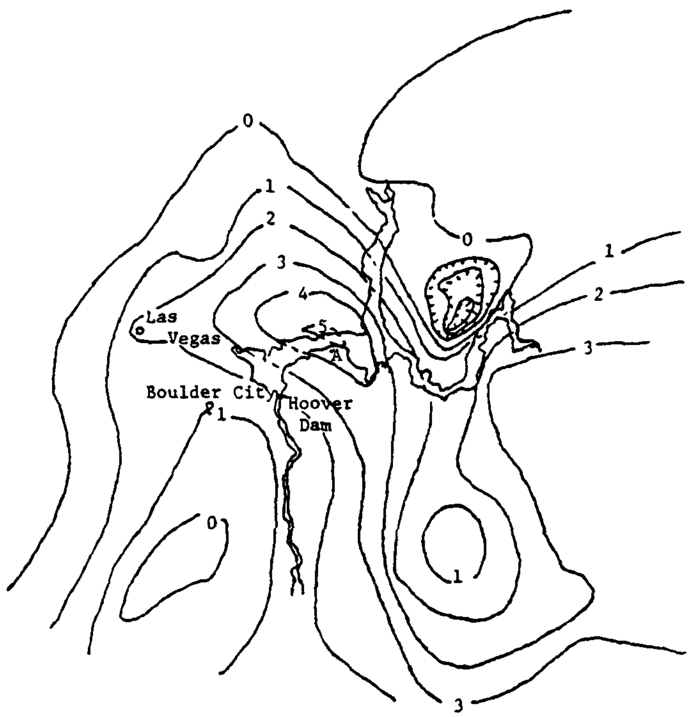


Figure 7. Settlement contours from 1941 survey
(after Raphael (1954))

near Boulder Canyon rather than at the Bonelli Basin. In the survey, Las Vegas begins to show depression due to groundwater table lowering. This settlement at Las Vegas will become more pronounced as time goes on. The Las Vegas displacement is taking place in the alluvium which veneers the crust and is not related to Lake Mead. The area northeast of Bonelli Basin is presumably rising, but the survey officials warn that this rise may be due to a survey error.

47. In the 1949 survey, the maximum settlement remains in Boulder Canyon, and the area northeast of Bonelli Basin begins to settle. An

area near Nipton and Searchlight begins to settle substantially for no reason. Raphael (1954) concludes that the region is tilting.

48. In the 1963 survey the entire region appears to rebound. Almost all points are higher than the 1949 survey. The net settlement from 1935 begins to look more like the calculated deflection pattern. The maximum settlement has moved southeast from Boulder Canyon to the head of Detrital Wash.

49. Such a general rise cannot be due to the lake and is evidence that other forces are at work, assuming that the survey is correct. To be compatible with an elastic model, the reservoir load must be proportional to the maximum deflection. The lake levels for all three relevelings, 1941, 1949-50, and 1963, are comparable. The load due to siltation can be estimated from the hydrographic survey of 1948-49 and 1963-64. The loads during the releveling are estimated at about 7.6, 7.2, and 8.0 times the load present in 1935. Though it is impossible to make point-for-point comparisons, there appears to be a general increase in settlement from 1941 to 1950 and a general rebound from 1950 to 1963. The estimated loadings are given in Table 4, and the settlement contours from the surveys are shown in Figures 7, 8, 9, and 10.

Table 4

Lake Mead Volume During Level Surveys

Month/Year	Water Level, ft	Volume acre-ft
Mar-Apr 1935	895-900	3.4×10^6
Oct 1940-Apr 1941	1160-1175	25.8×10^6
Dec 1949-Jul 1950	1150-1175	24.6×10^6
Apr-Jun 1963	1170-1185	27.2×10^6

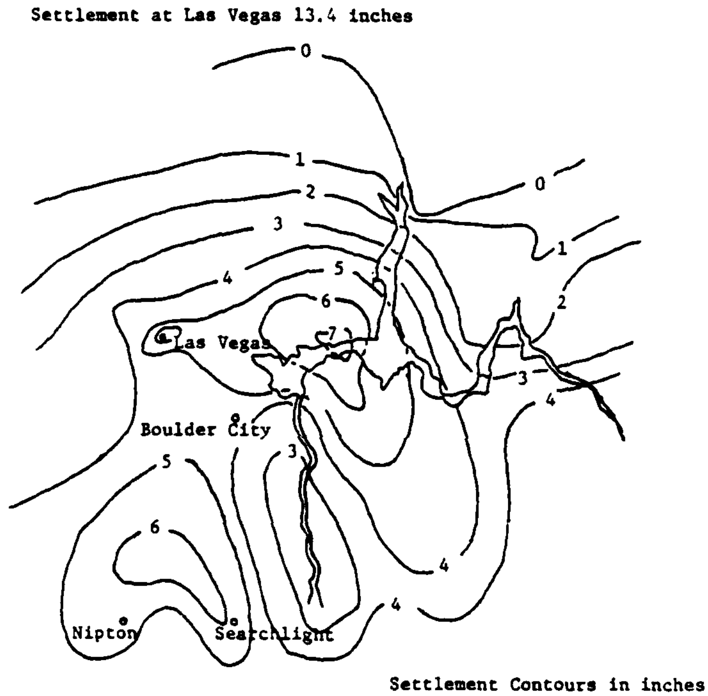


Figure 8. Settlement contours from 1949-50 survey
(after Raphael (1954))

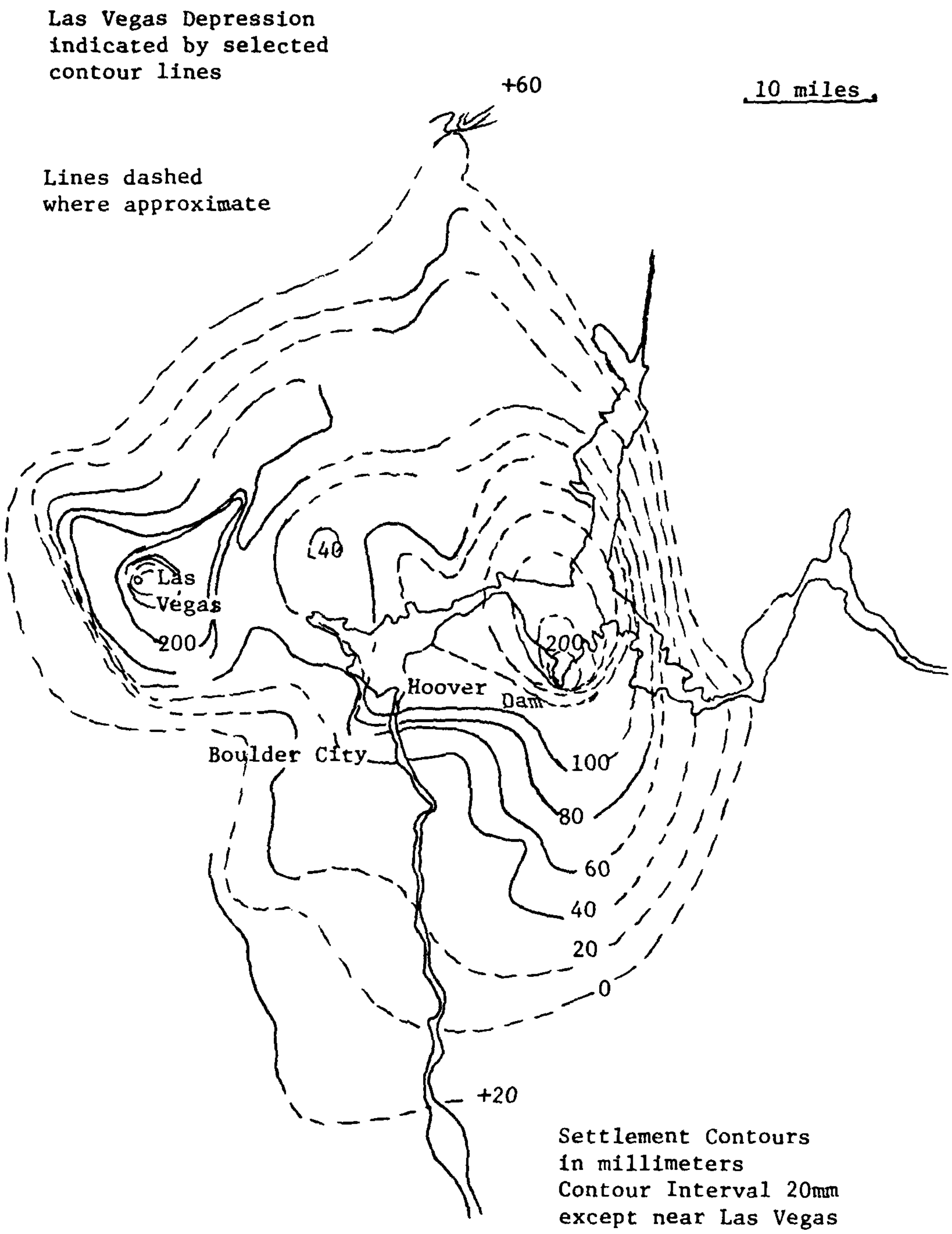


Figure 9. Settlement contours from 1963 survey (after Lara and Sanders (1970))

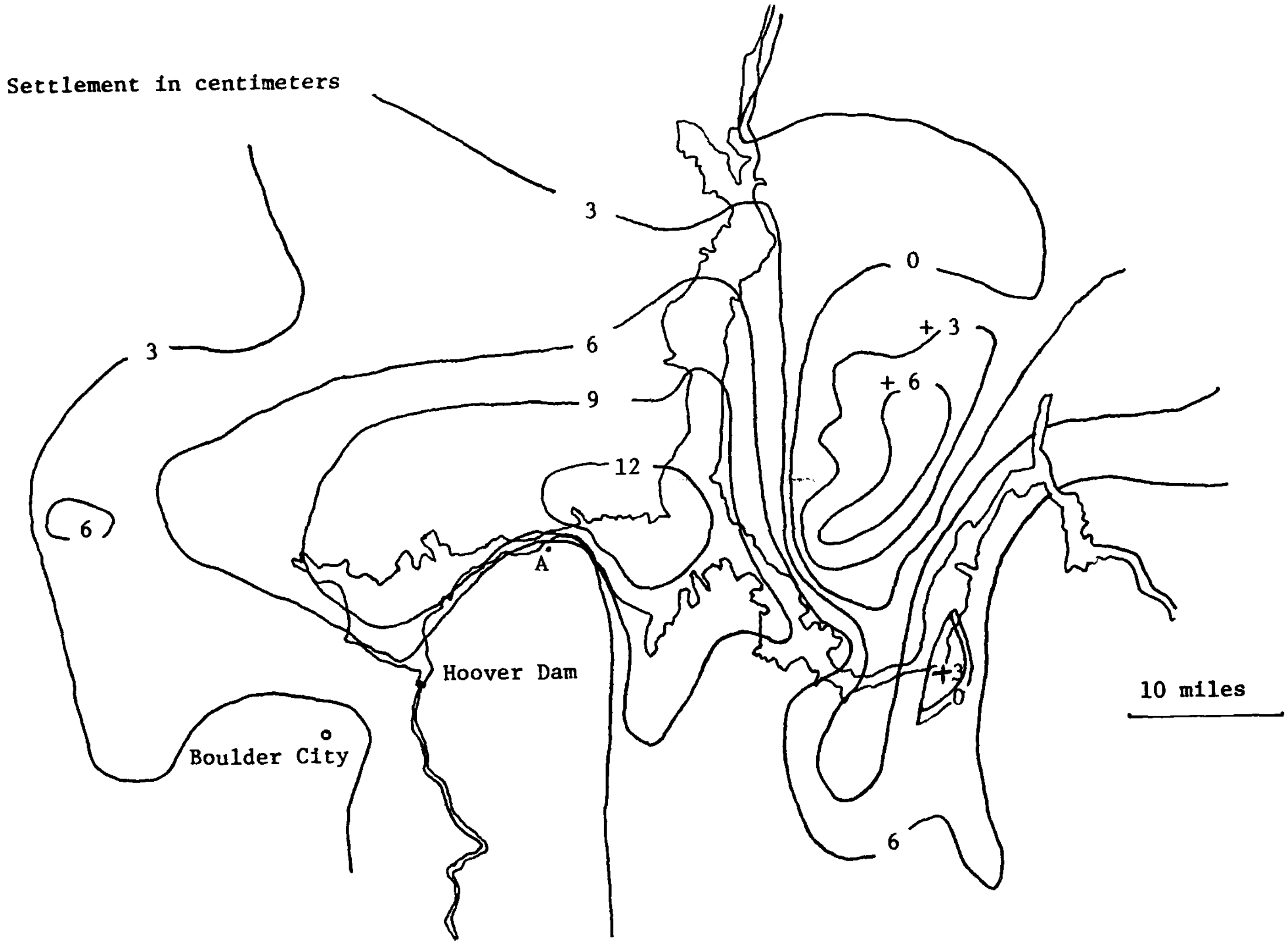


Figure 10. Settlement contours at Lake Mead from 1941 survey, alternative (after Carder and Small (1948))

50. The figures showing actual settlement contours are misleading. The contours are drawn from the field survey data. Except where contours go through a benchmark, the location of the contour line is determined by interpolation between actual point values measured at benchmarks. The process of interpolation requires the draftsman to approximate how the settlement value varies between points. The approximation can be done with a degree of confidence for contours of surface topography where the ground surface between points has been observed. Contouring predicted settlement based on theory can be done since the theory indicates how the settlement varies between any two points. Since the predicted settlements can be contoured, the draftsman can see how the contours are supposed to look. The extent to which the bias of the draftsman has influenced Figures 7 through 10 is unknown. Notice point A on Figures 7 and 10. Both of these figures represent the 1941 survey results. In Figure 7, A is within the 4-in. (≅ 10-cm) contour, but in Figure 10, A is outside the 6-cm contour. Considerable interpolation is required to draw these contours, and it is remarkable how generally similar both figures are. The settlement pattern conforms roughly to the expected pattern.

51. A better test of the prediction of deflection is the examination of long level lines as was done at Kariba. The relevelling done at Lake Mead did not produce the excellent agreement with theory seen at Kariba. Only certain lines were releveled in 1963, and of those, several were influenced by the subsidence at Las Vegas caused by groundwater extraction.

52. Several lines remain available for checking the elastic deflection. The lines are labeled IX west, IX south, X south, XI west, and XI south, as shown in Figure 6. Settlement profiles along these lines are presented in Figures 11 through 15. A review of these figures shows that 1941 and 1963 surveys are in general agreement, while the 1949 survey is generally 6 to 10 cm lower. The conclusion drawn by Lara and Sanders (1970) is that the Lake Mead area was rebounding from 1949 to 1963.

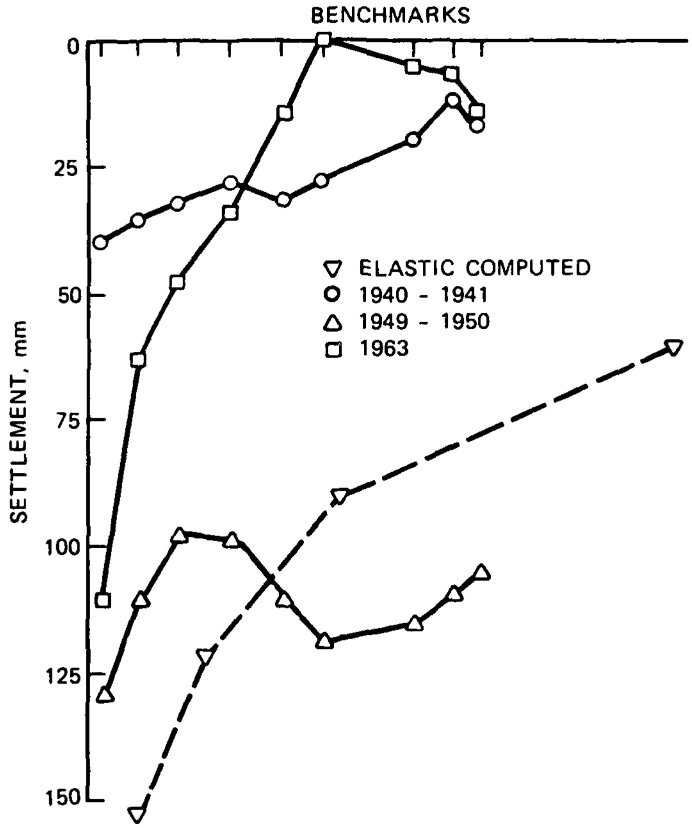


Figure 11. Settlement profile line IX west

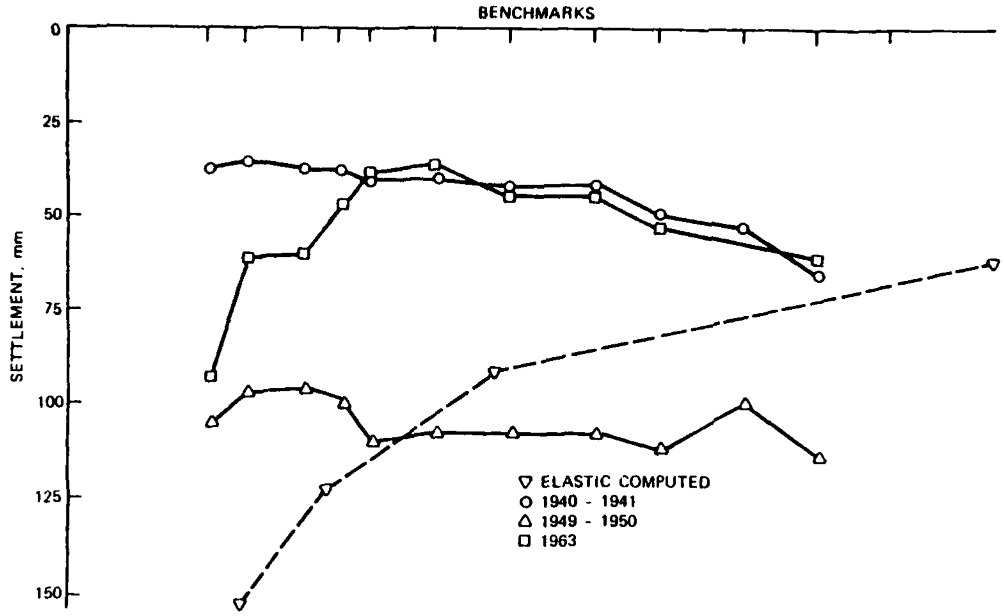


Figure 12. Settlement profile line IX south

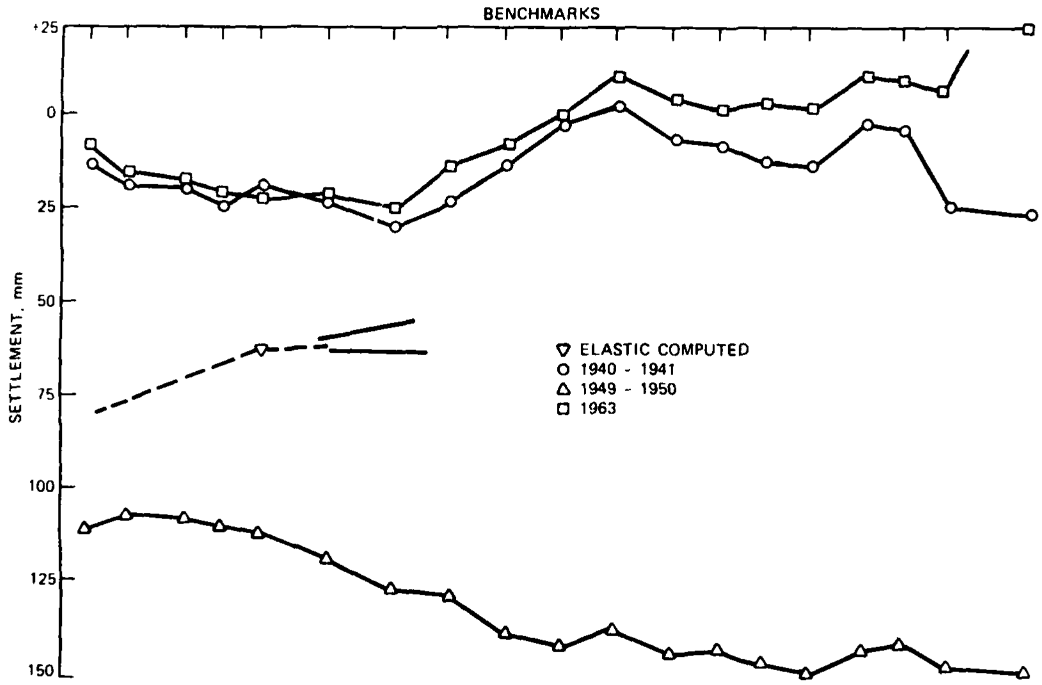


Figure 13. Settlement profile line X south

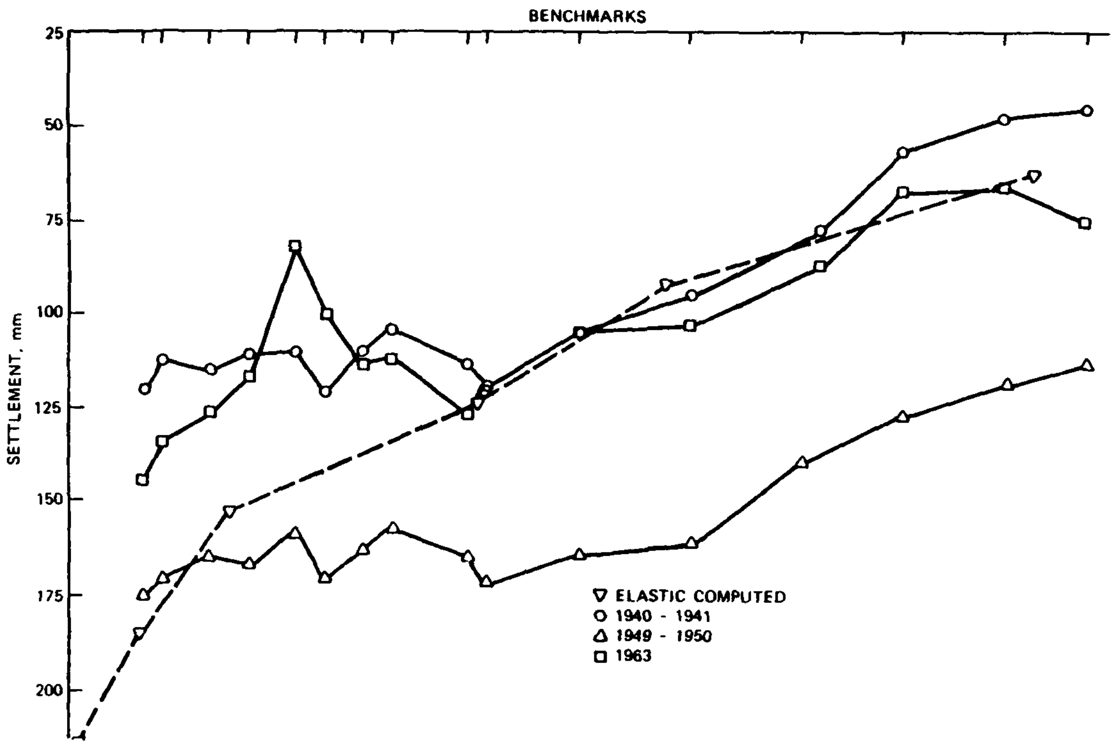


Figure 14. Settlement profile line XI west

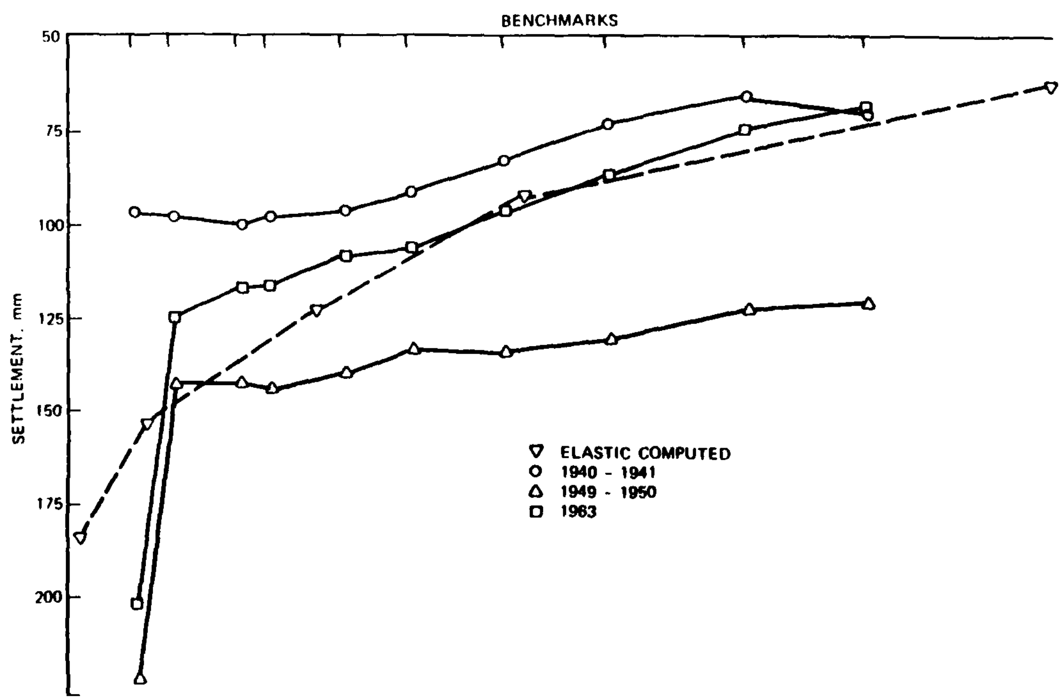


Figure 15. Settlement profile line XI south

53. The predicted deflection along each line is shown in the figures. The choice of modulus will influence the shape of the curve. Adjustment of the predicted deflection curves by a modulus factor can provide improved fits for some curves, but the predicted curves generally have a poor fit with the actual data. The crust may perform elastically, but the simple homogeneous model is a poor approximation of the actual conditions.

54. The crust is elastic if the strains are recoverable. Although the crust appears to be rebounding, the reservoir load is not any less in 1963 than in 1949 and is probably greater. The load estimates shown in Table 4 are close enough that it is not clear that the 1949 loading was the lightest of the three survey periods. One line does provide a clearer picture of relative loads. Line X south runs from a point about 10 miles southwest of Boulder City south to Searchlight. This line is rather remote from Lake Mead and shows little change in elevation from 1935 in either the 1941 or 1963 survey. The 1949 survey shows about a 10-cm drop along the line, and conversely there is about a 10-cm rise (or rebound) from 1949 to 1963. This line roughly parallels the Colorado River below Lake Mead at a distance of about 14 miles.

55. Further down on the Colorado River, Davis Dam was built during the forties and completed in 1953. Davis Dam impounds Lake Mohave, which runs from the tailwater of Hoover Dam to Davis Dam about 68 miles downstream. The 1949 survey was performed from December 1949 to July 1950. During January 1950, Lake Mohave was filled to about an elevation of 570 ft and contained about 220,000 acre-ft of water. After 1953, Davis Dam operated near elevation 640 ft and contained nearly 1,880,000 acre-ft of water. Lake Mohave extended north of Searchlight and should be considered as an increase in load, near line X south from 1949 to 1963. Despite the increase, line X rose 10 cm from 1949 to 1963. Since there was no decrease in load, the change in elevation does not represent elastic rebound. Instead the crust could be responding to changing forces within the crust rather than a change in boundary loadings, or the crust is behaving as a two-phase media. These possibilities must be considered when evaluating the induced seismicity at Lake

Mead. The survey data indicate that a simple single-phase (dry) homogeneous elastic model is an inadequate representation of the crust at Hoover Dam.

56. In a later survey at Kariba, an apparent rebound is shown by the relevelling (Figure 16). This implies that the use of a simple

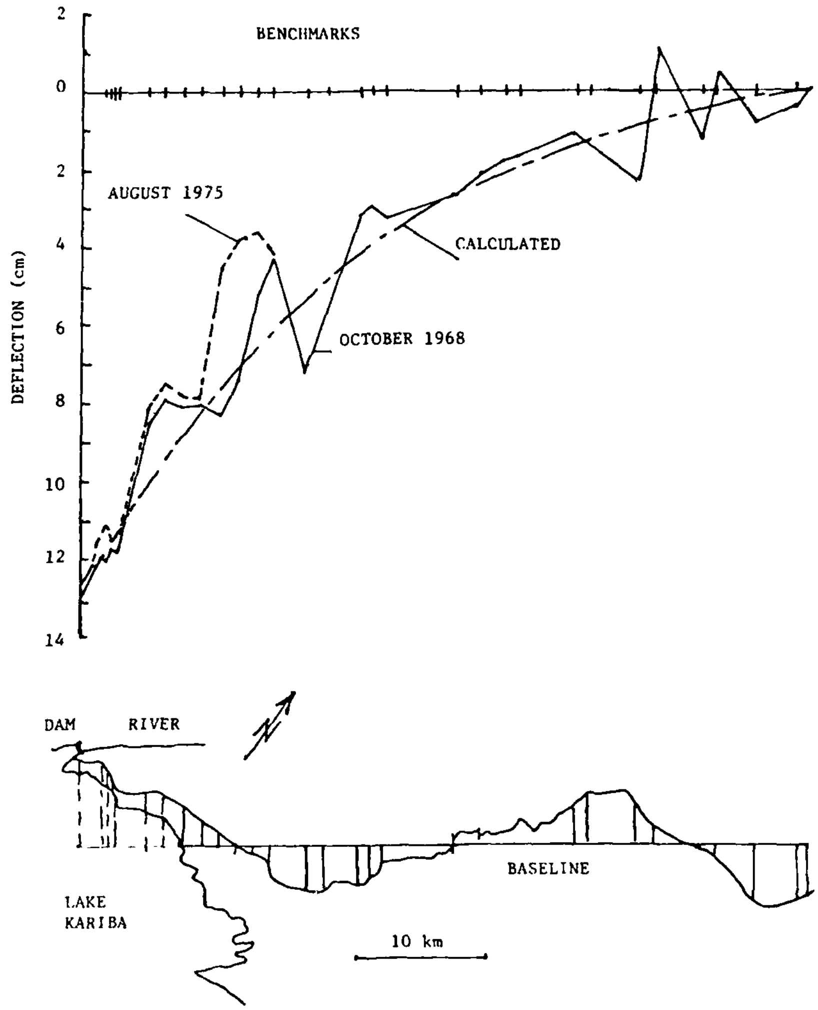


Figure 16. Settlement profile from Kariba to Makuti, 1975 (after Withers (1977))

homogeneous elastic crustal model may be inadequate to predict stresses. Elastic theory provides a way to translate water load to crustal stress, but the predicted stress distribution will not be accurate in cases where a simple single-phase model is inappropriate.

Fluid injection case histories

57. Fluid injection or water flooding can provide information concerning the areal extent of earthquakes triggered by high fluid pressures. The magnitude of the fluid pressure at the point of injection and the location of the zone of the applied increase is known. Induced earthquakes can be located relative to the point of injection. The cases selected for discussion are among the best known and best documented.

Rocky Mountain Arsenal

58. During 1961, an injection well was drilled to a depth of 3.67 km bottoming in Precambrian crystalline rocks. Fluid injection began on 8 March 1962 and continued until 30 September 1963 at an average rate of 21 million litres per month. No fluid was injected from October 1963 to August 1964. Then injection resumed under gravity flow and was accepted at a rate of 7.5 million litres per month. Injection under pressure resumed on 6 April 1965 at a rate of 17 million litres per month. All fluid injection stopped on 20 February 1966. The earthquakes that were attributed to the fluid injection were located within 10 km of the injection well. The distribution of the events was not symmetrical and did not appear to migrate with time. The zone of earthquakes had a well-defined southern boundary but no distinct northern boundary. The three largest events were Richter magnitude 5.0, 5.2, and 5.3, and all occurred about 6.5 km west-northwest of the disposal well. All three of these earthquakes occurred more than a year after all injection had ceased.

Rangely Oil Field

59. Fluid injection into Weber sandstone in Colorado for secondary recovery of oil has been practiced since 1957. The fluid pressures near the perimeter of the oil field have risen from about 240 to 275 bars, about 100 bars greater than the normal hydrostatic pressure of about 170 bars, according to Raleigh, Healy, and Bredehoeft (1972). Small events presumed to be caused by the fluid injection have occurred at distances up to 4 km from the perimeter of the field. The largest events ranged from magnitude 4 to 4.5.

Matsushiro, Japan

60. The Japanese carried out a bold experiment in fluid injection in central Japan. The stated purpose of their program was to determine whether earthquakes could be induced by increasing pore water pressure. No other case is known to this writer where the fluid injection was used solely to induce earthquakes. A well, 1.8 km deep, was drilled into igneous basement rock. The Matsushiro area was the scene of earthquake swarms in August 1965 and April 1966. The well may have encountered the Matsushiro fault at a depth of 1000 m. The geological section of the the well is shown in Figure 17. The pumping pressure in the well ranged from 14 to 50 bars. The injection was performed during two periods. For 3 days, starting 15 January 1970, a pressure of 50 bars was applied to pump 32.4 m^3 of water. A second period of injection began on 31 January and continued to 13 February under pressures that ranged from 14 to 23 bars. The vicinity of the injection well was carefully monitored. The hypocenters of the induced earthquakes were determined. The events triggered by the injection clustered in a rectangular area of about 5.5 km by 4.0 km. The events were within 4.0 km of the injection well as shown in Figure 18.

Other cases

61. Near Dale, N. Y., a high-pressure injection well used in salt mining induced earthquakes in a 5-km zone roughly parallel to the strike of the nearby Clarenden-Linden fault. Also, induced earthquakes have occurred as aftershocks in underground explosives testing. The nature of this phenomenon is somewhat different than the supposed mechanisms at work in reservoir-induced seismicity. The extent of aftershock zones from blast tests is not a reasonable measure of the areal extent of supposed reservoir-induced seismicity.

62. Fluid injection does not always induce earthquakes. The geologic setting must be appropriate or earthquakes may not be induced despite the application of high pressures. A study was performed at the site of a brine injection well at Childress, Tex. (Patrick 1977). A seismicity study began in July 1970. The first trial injection took place in April 1972. The monitoring was continued until June 1975. The

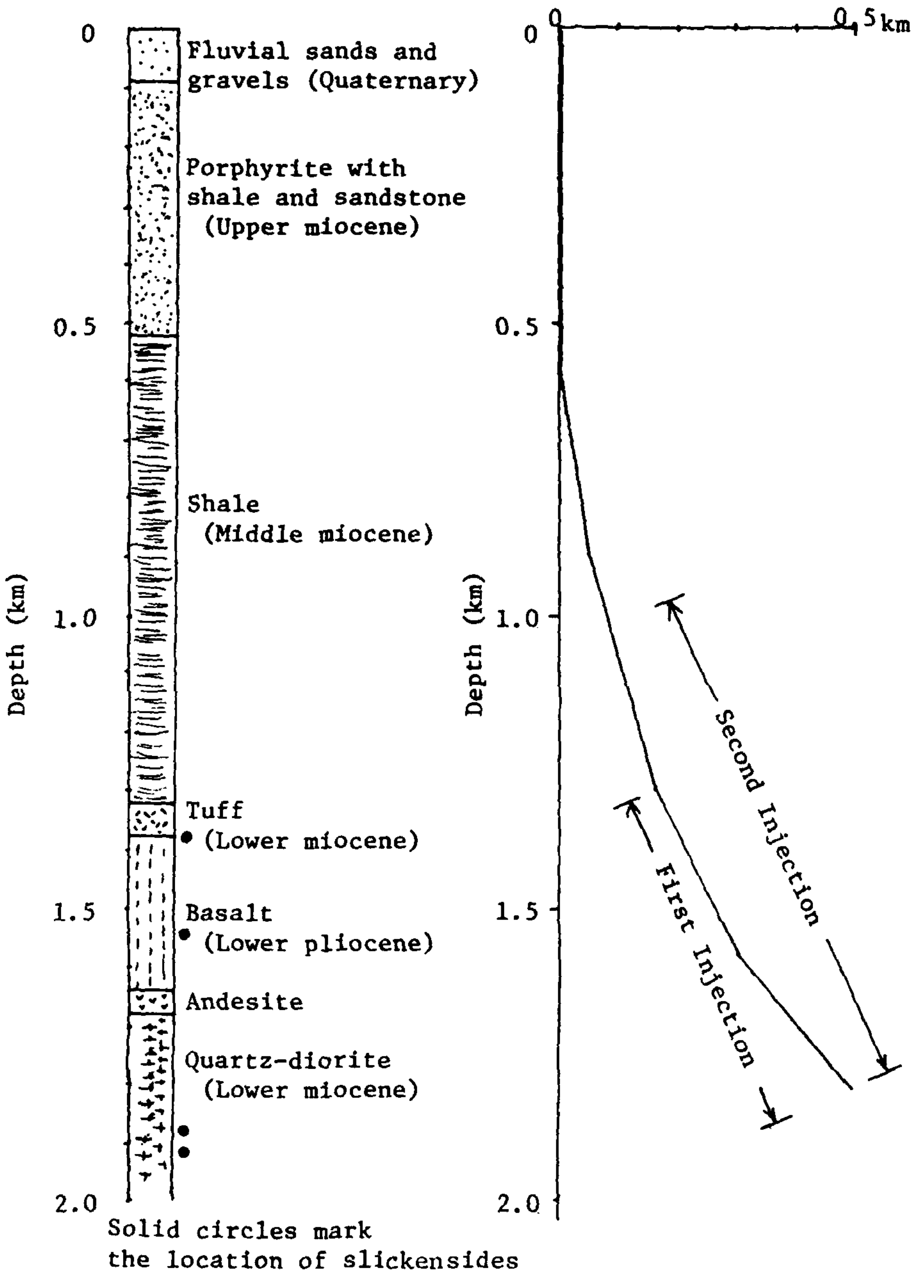


Figure 17. Log of injection borehole at Matsushiro (after Ohtake (1974))

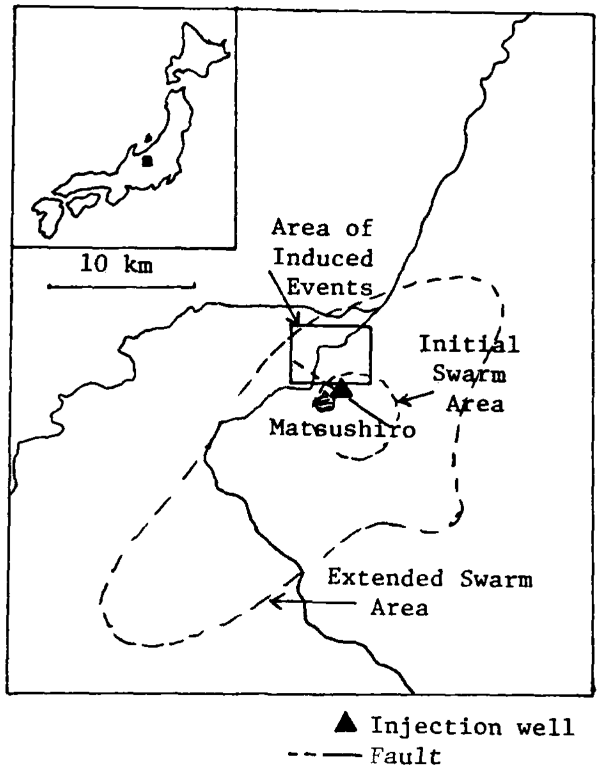


Figure 18. Region of Matsushiro earthquakes (after Ohtake (1974))

area displayed almost no seismic activity during the entire monitoring period. Fluid injection does not automatically induce seismic events, although it may under the proper set of conditions. Cases which appear to be induced seismicity from fluid injection are the Rocky Mountain Arsenal, Rangely Oil Field, and Matsushiro, Japan.

Conclusions based on empirical data

63. The volume of the crust influenced by reservoir cannot be reliably estimated solely by theoretical considerations. The heterogeneity of the crust is too difficult to reduce to a simple model, and it is the heterogeneity of the crust that profoundly influences the manner in which the crust adjusts to the reservoir. Earthquakes induced by fluid injection are apparently the result of the same mechanism thought to work in reservoir-induced seismicity. For this purpose of estimating

the areal extent of increased fluid pressure, three well-documented cases of fluid injection were examined.

64. Certain differences between fluid injection and impoundment of a reservoir are the duration of the pressure increase and the location of the applied pressure increase. The pressures used in fluid injection are generally much higher than those imposed by reservoirs, but the duration of the fluid injection generally occurs for a shorter period than the more or less permanent increase caused by impoundment. Despite these acknowledged differences in the processes, these three cases imply that the zone of influence ranges from 4 to 17 km from the point of applied fluid pressure increase. If no geologic information indicates otherwise, the area within 20 km of the reservoir boundary will be considered to define the area of influence of the reservoir. The selection of 20 km is based on empirical evidence drawn from case histories of fluid injection. The choice of 20 km, versus 21 or 18 km, for example, is arbitrary. Where the precise location of the boundary of the zone of influence is critical, geotechnical evidence might be used to refine the location.

65. The selection of the boundary of the area of influence is the first step in making a catalog. The goal is a catalog that lists all events larger than a reference magnitude that occurred within the area of influence during a specified time period. The reference magnitude is called the minimum magnitude of complete detection, M_{md} .

PART III: TYPES OF EVIDENCE--STRENGTHS AND LIMITATIONS

66. The assessment of the impact of the reservoir on local seismicity requires the selection of a measure of seismicity and a method by which a change in the selected measure of seismicity can be evaluated. All the types of evidence listed in Part I consist in part of a measure of seismicity. Basic catalog information was discussed in Part II. This chapter explores the consequences of adopting specific measures of seismicity. The discussion is organized under the evidence types presented in Part I.

Postimpoundment Change in Seismicity

67. This type of evidence consists of a measure of seismicity which is evaluated for two time periods--one period prior to impoundment and the other period after impoundment. The seismicity values for these periods are compared. If the reservoir impoundment has no effect on the seismicity, the two values should be roughly equivalent. The method used to compare the two values is a statistical test. This section discusses the details of selection of a measure of seismicity and appropriate statistical methods available to detect change in the selected seismic parameter.

Statistical Model

68. The goal of a hypothesis test is to make inferences concerning the null hypothesis. The inferences are possible because of assumptions made about the way the data are distributed. These assumptions constitute a statistical model. The assumptions must be consistent with the physical process which the data represent. Earthquakes are considered to be energy releases. It is not reasonable to model earthquake occurrence with a distribution that may take on negative values, or to use a model that predicts as many high magnitude events as low magnitude events. This is not consistent with observed behavior.

69. A large body of statistical tests are based on the normal distribution. The assumption of normality or any other distribution should be founded on prior knowledge concerning the phenomena. If a particular distribution is assumed, the assumption should be checked using a goodness-of-fit test. Regardless of the outcome of a goodness-of-fit test, the underlying assumptions of the distribution should be examined to determine whether they are compatible with the physical process that is being modeled.

70. Almost all distributions require time independence. Seismicity would be time independent if the occurrence of an event during the observation period does not influence the occurrence of an event during any other period. Earthquakes are clustered in time and violate any assumption of time independence. Aftershocks are due to the occurrence of a prior event. Foreshocks are related to an event that occurs later in time. Any statistical model that relies on time independence must use data that have been modified to remove foreshocks and aftershocks. Foreshocks and aftershocks often are identified by employing some arbitrary criterion using both the time of occurrence and location information. This modification of the data typically entails representing an earthquake sequence by one event whose magnitude corresponds to the largest event in the sequence. This practice is reasonable considering that the main shock often contains almost all of the energy released in the earthquake sequence. The above procedure was used in handling the data in the example of the previous section (see Table 2). If the energy of the sequences spreads among several events, some other strategy should be employed.

71. Another attribute of statistical models is their dimensionality. Since the vast majority of statistical models are univariate, the seismicity, a five-variable quantity, must be reduced to univariate data. This reduction in dimension has severe consequences. Even if a bivariate model is adopted, only the bivariate normal has a suite of well established statistical methods to use in hypothesis testing. In testing independence, Kendall's statistic and Spearman's rank correlation offer alternatives to assuming a bivariate normal distribution.

The bivariate normal is seldom, if ever, appropriate in dealing with seismicity. Considering multivariate statistics, only the multivariate normal is widely used, and it is not appropriate for this subject. The problem in general is the requirement to reduce the dimension of the seismicity.

72. Univariate models are preferred because these simple models permit use of well-known statistical tests. Seismicity is usually reduced to univariate data by limiting the data to a given geographical area and time period. Once this is done the location information is no longer used and one of two types of data is evolved: (a) time is used to further segregate the data into preimpoundment and postimpoundment periods in which the data are treated as two samples of magnitude data and (b) the magnitudes are ignored and all earthquakes are treated as equal. Then the occurrences are grouped by time into preimpoundment and postimpoundment periods and the number of occurrences is treated as the univariate data. Other treatments will be discussed, but it should be noted that the two treatments just described are by far the most common.

73. Again, look at the data in Table 2. These earthquakes were all located within 25 km of the dam. No further location information is provided. The time record runs from 1932 to 1978. Events certainly occurred before 1932 and after 1978, but the notion of time independence permits any portion of the record to be examined. However, spatial independence is not assumed. The physical mechanism of earthquake generation makes it clear that the spatial distribution is very nonuniform. One location is obviously different from another. Consequently, when two separate areas are compared, the fact that the seismicity of these two areas is equivalent should not be used as a null hypothesis. It is accepted that it is very unlikely that two separate locations will have the same level of seismicity.

Hypothesis testing

74. The manner in which the hypothesis is stated can make the difference between an untestable hypothesis and a testable one. The null hypothesis is the statement whose credibility is being tested. In this study the general form of the null hypothesis is "There is no change

in the level of seismicity" versus the alternate hypothesis "There is an increase in the level of seismicity." It is also possible to use an alternate hypothesis "There is a decrease in seismicity." This latter case generally is not investigated.

75. The attractiveness of hypothesis testing is that it quantifies the credibility of the null hypothesis. The hypothesis testing is performed using an alpha (α) level of 5 percent for one-sided alternatives and 10 percent for two-sided alternatives. The alpha level determines the significance of the test. It represents, in the long run, the number of times that the null hypothesis would be rejected when it is correct. It is a measure of the conservatism of the tester. The P-values are also reported. This P-value is the alpha level at which the hypothesis would barely be rejected. An alternative definition is that the P-value is the probability that under the null hypothesis, data exist more extreme than observed. The alpha level indicates the limit on what is referred to as a Type I error. This error is the rejection of a true hypothesis. There is another type of error which has not yet been addressed. This error, labelled a Type II error, is failure to reject a false hypothesis. To get an idea of the size of this error, the question "How small a deviation from the null hypothesis can be detected?" must be answered. For example, say the null hypothesis is that the preimpoundment rate of earthquake occurrence is equal to the postimpoundment rate. If in fact the postimpoundment rate were 10 percent higher, would a given test reject the null hypothesis? The size of the Type II error is a function of the desired sensitivity, the distributional assumptions, and the test statistic and the amount of data and its accuracy. In general, it will not be possible to get an accurate determination of the likelihood of committing a Type II error. The existence of Type I and II errors prevents the tester from concluding that a failure to reject a hypothesis establishes the truth of the hypothesis.

76. Failure to reject the null hypothesis does not mean it is true. It does mean there is not sufficient evidence to reject it. It is analogous to a trial court case where the jury may not find one guilty so long as there exists a reasonable doubt. A verdict of not

guilty (failure to reject) does not prove that the accused did not commit the crime.

Test statistic

77. The test statistic is a quantity that results from a transformation of the data. This quantity has a particular distribution under the null hypothesis. The test statistic assumes this distribution exactly or approximately. If the test statistic assumes the exact distribution, then the only error present lies in the validity of the assumptions underlying the null hypothesis. If the test statistic follows a given distribution approximately, the fact that it is approximate should be recognized and stated by the tester. In some instances, the distribution of the test statistic is generated from the data. Because of this direct dependence on the data, tests of this nature are called "conditional." In all cases, the test statistic gives the likelihood that the observed data could occur, assuming the null hypothesis were true.

78. A number of statistical models will be discussed. In particular, each model will be reviewed to compare the assumptions of the model to the physical mechanics of seismicity. Hypothesis tests will be formed as examples using the data from Table 2. The discussions involve too many variables to be uniquely represented by the same letter throughout the remainder of the text. The notation for each model is defined in the text and applies only within the section.

Poisson distribution

79. The Poisson distribution frequently is used to model earthquake processes. The model has been used to depict the distribution of a given magnitude about a mean and to approximate the time distribution of earthquakes. Considerable work has been done in describing the uses and shortcomings of the Poisson model. In particular, the work of Utsu (1961), Lomnitz (1966), and Savage (1975) are pertinent.

80. The Poisson process requires four assumptions. Following the presentation of Savage, these assumptions will be introduced as axioms. Let ℓ be a continuous interval (usually time) with events r taking place in interval ℓ, and let $N(\ell)$ be the number of events that have

taken place over the interval $(0, \ell)$. The axioms are as follows:

a. Axiom 1. The process $N(\ell)$, $\ell \geq 0$ has independent increments. That is, the number of events occurring in any one increment has no effect on the number of events occurring in any other increment.

b. Axiom 2. For any $\ell \geq 0$, the probability that an event will occur during a given interval $d\ell$ is equal to $\lambda d\ell$ where λ is a constant greater than zero; λ is the average number of events per unit ℓ .

c. Axiom 3. For $\ell \geq 0$ it is not possible for more than one event to occur at exactly the same value of ℓ .

d. Axiom 4. $N(\ell)$ is stationary. That is, the distribution of $N(\ell)$ is the same over any increment of ℓ .

81. The Poisson model is used with two univariate definitions of seismicity. Recall that seismicity is a five-parameter variable, but the Poisson model is a univariate model. The two most common operational definitions of seismicity measure the number of occurrences over time and the frequency of occurrence as a function of magnitude. Both definitions require that all events are independent. This requires identification and removal of dependent events. Once this is done, some other problems must be recognized and considered. The Poisson model is inadequate in several respects. The shortcomings will be grouped in accordance with the operational definition of seismicity.

Magnitude-frequency definition

82. The magnitude frequency is usually depicted on a semilogarithmic plot in the form $\log N = a - bM$. The magnitude-frequency relationship is also called the recurrence relationship. The method used to estimate b can have a great influence on the actual value calculated. The plot of the recurrence relationship should be a straight line, but frequently appears to be linear in only a portion of the plot. Occasionally, the recurrence relationship has no linear portions. A typical representation is shown in Figure 19. The curve is divided into three sections called low magnitude, section I; moderate magnitude, section II; and high magnitude, section III. To account for the nonlinearity, reasons advanced by several researchers are summarized below:

a. Section I.

(1) This is evidence of a threshold magnitude below which energy can be stored in the crust.

(2) Some low magnitude events are undetected.

(3) There is bias in magnitude assignment due to detection device characteristics.

b. Section II.

(1) Unusual geologic conditions occur.

(2) The catalog contains too few events to characterize the recurrence relationship.

(3) There is a magnitude bias.

c. Section III.

(1) There are regional maximum magnitude limits.

(2) The limited period of observation was too short for such rare events.

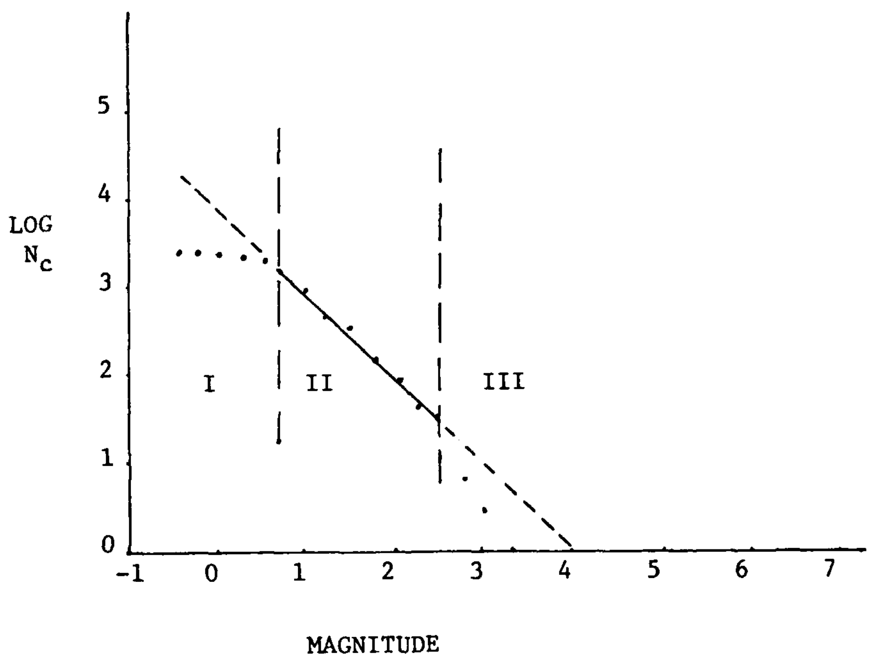


Figure 19. Recurrence relationship

83. The nonlinearity indicates a linear recurrence relationship may not be appropriate. Any of the (2) and (3) reasons may be explained

away as sampling errors and the model remains valid. Any of the (1) reasons mean that a linear expression inadequately models the physical process. Consequently, the model is inappropriate to use with data that display nonlinear behavior and is applicable only as an approximation of data exhibiting the linear behavior.

84. Two methods of constructing a recurrence curve are practiced--(a) The logarithm of the number of events in each magnitude group is plotted versus magnitude; (b) the logarithm of the cumulative number of events with a magnitude greater than some reference magnitude is plotted versus the reference magnitude. The number of events, N, occurring in an increment of magnitude, $M \pm \Delta M$, has been shown to be Poisson-distributed with a mean of $10^a 10^{-bM}$ (Utsu 1971, Savage 1975). The cumulative number of events greater than some reference magnitude is also Poisson-distributed due to the additive property of Poisson variables.

85. Utsu (1965) suggested a method to calculate the b value. Aki (1965) showed that this method produced the maximum likelihood estimate of the b value. Utsu (1966) obtained the probability density function of the b value and demonstrated that the ratio of two b values is F-distributed.

86. The null hypothesis (H_o) is that there is no change in seismicity. The alternative hypothesis (H_a) is that there has been an increase in seismicity. The b value is used to represent seismicity. This definition is frequently used but is not meaningful from an engineering viewpoint:

$$H_o: \; b_{post}/b_{pre} = 1$$

$$H_a: \; b_{post}/b_{pre} > 1$$

b_{post}/b_{pre} is F-distributed with $(2 \times n_{post}, 2 \times n_{pre})$ degrees of freedom (dof) where n is the number of earthquakes observed.

From Figure 2 $\quad n\ post = 7 \quad n\ pre = 8$

$F\ crit = F_{0.95}\ (14,\ 16) = 2.37$

Reject H_o if $b_{post}/b_{pre} \geq 2.37$. Use the maximum likelihood formula to calculate b.

$$b_{post} = \frac{n\ (0.4343)}{M - nM_{min}} = \frac{7(0.4343)}{27.60 - 7(3.45)} = \frac{3.04}{3.45} = 0.88$$

$b\Delta M = 0.88\ (0.1) = 0.088 \quad K = 1.004 \quad b = 0.88 \quad k = 88$

$$b_{pre} = \frac{n\ (0.4343)}{\Sigma M - nM_{min}} = \frac{8(0.4343)}{33.90 - 8(3.45)} = \frac{3.47}{6.30} = 0.55$$

$K = 1.0$

$$\frac{b_{post}}{b_{pre}} = \frac{0.88}{0.55} = 1.60 < F_{0.95}\ (14,\ 16)\ \text{fail to reject}\ H_o$$

87. A test of $b_{post} - b_{pre}$ is also possible. This test treats b as a regression coefficient and assumes that the distribution of b is nearly normal.

Time-frequency definition

88. When earthquakes are modelled as a time frequency, the parameter used in the Poisson model is the average number of events occurring per unit of time. This parameter is in virtual lockstep with the detection level. The magnitudes of the events have no bearing on the model. As a result, it is imperative that the data be examined carefully to ensure the data are adequately modelled by the Poisson distribution. The detection level must remain constant over the entire sampling period. Specifically, the average number of events is approximately a function of the minimum magnitude which is fully detectable.

89. As before, the events must be independent. The record should be edited to pool dependent events. This can be a difficult task particularly for magnitudes from 0 to 4. In this range two types of dependent events occur. One is the aftershock sequence. This is typified by

occurrence of a moderate size event $M \approx 4$ and a collection of smaller events triggered by the largest event. The other type of dependent event is the microearthquake cluster. This is a sequence of events with no single event that can be identified as a main or triggering event. Consequently, this behavior is more difficult to detect. For a detailed explanation of clustering, see Savage (1975).

90. A test similar in form to the one for magnitude frequency is possible for time frequency. The operational definition of seismicity in this test is rate (number of events per period of observation). Call the rate λ, and

$$H_o: \ \lambda \text{ post}/\lambda \text{ pre} = 1$$
$$H_a: \ \lambda \text{ post}/\lambda \text{ pre} > 1$$

91. This is also F-distributed with the dof (2 × number of post events, 2 × number of pre events). So as before, $F \text{ crit} = F_{0.95}(14, 16) = 2.37$, and

$$\frac{\lambda \text{ post}}{\lambda \text{ pre}} = \frac{7/20}{8/28} = \frac{0.35}{0.29} = 1.23 < F_{95}(14, 16) \text{ fail to reject } H_o$$

92. Both the test of b values and the test of time frequency use an F statistic to test the null hypothesis. In both cases the dof's for the F statistic were determined by the number of events which had occurred. Tests are possible with as few as two events in each period for the magnitude-frequency test and one event per period in the time-frequency test. It is very difficult to detect differences until a sizable number of events are recorded in each period. In the case of time frequency the length of the period of observation is not as important as the number of events recorded. Examination of the F distribution brings out these points. If the preimpoundment record has only one event, then about a twentyfold increase in rate of occurrence is required to reject H_o. If there were two pre-events, then about a sixfold increase is required. To reject the null hypothesis based on a doubling of the rate of occurrence at least nine events would have to be recorded.

This assumes an alpha of 1 in 20. In this example, about 13 events would be required in the 20-year postimpoundment observation period to reject H_o.

$2 \times 2\ \chi^2$ test

93. Another way to use a contingency table is to use a goodness-of-fit approach. The assumption required is that the occurrence rate of events, R, is constant. Then the number of events observed should be proportional to the length of the observation period. The test uses a time-frequency definition of seismicity. For these data,

X_{post}	X_{pre}
E_{post}	E_{pre}

where E is the expected number of events under the null hypothesis, which was that the occurrence rate was constant. H_o: $R_{post} = R_{pre}$,

$$R = \Sigma X/\text{length of observation} = 15 \text{ events}/48 \text{ years}$$

$$E_{post} = \frac{15}{48} n_{post} = \frac{15}{48}(20) = 6.25 \qquad E_{pre} = 8.75$$

7	8
6.25	8.75

The test statistic is approximately χ^2 distributed with 1 dof:

$$\chi^2_{95} = 3.84 \qquad \text{Compute } \chi^2 = \sum \frac{(X - E)^2}{E}$$

$$\chi^2 = 0.15 \ll \chi^2_{95} \qquad \text{P-value} = 0.85 \text{ (unusually high)}$$

Magnitude shift

94. Up to this point the operational definition of seismicity was based on magnitude-frequency relationships or time-frequency relationships. It may be desirable to use an operational definition of seismicity based on the size of the energy release rather than its time frequency or relative magnitude frequency. The b value describes the relationship between the frequency of small events compared to the

frequency of large events, but says nothing about the average size event per unit time. The time-frequency definition describes how often an energy release will take place with no reference to the size of the energy release. Neither of these two definitions is appropriate to engineering interests. The structures required to impound a reservoir are designed with due consideration given to earthquake loads, which are functions of the size of the energy release. A more appropriate operational definition may be the size of the energy release. The null hypothesis is then H_o: $\tilde{M}_{post} = \tilde{M}_{pre}$ where $\tilde{M}$ is an average magnitude or median magnitude. The preimpoundment and postimpoundment catalog provides two samples assumed to come from the same population. Using conventional statistical techniques, a t-test would be employed. However, the t-tests require that the data come from a near-normal population. The known distribution of magnitudes is, more or less, a negative exponential. This is severely nonnormal and the use of the t-test is totally inappropriate. Simple distribution-free tests are available to test this hypothesis.

Two-sample Wilcoxon

95. This test has a very simple model. There are N observations of magnitude, m from the preimpoundment period and n from the postimpoundment period. The magnitude determinations are assumed to be independent of one another and come from the same continuous population. It does not matter what is the form or what are the characteristics of the underlying population. It could be normal, exponential, or even uniform. The test goes as follows. Magnitudes from the preimpoundment period are labelled X_i, and Y_i are the postimpoundment magnitudes, such that

$$X_i = e_i \text{ , } i = 1 \text{ , } \dots \text{ , } m$$
$$Y_i = e_{m+j} + \Delta \text{ , } j = 1 \text{ , } \dots \text{ , } n$$

where the X and Y are observable magnitudes, e equals unobservable random variables, and Δ is a shift assumed to be due to the reservoir:

$$H_o\text{: } \Delta = 0;\ H_a\text{: } \Delta > 0$$

All magnitudes are ordered from least to greatest. Then sum the ranks of the Y's (postimpoundment). This is the statistic W. If $W \geq w$ (α, m, n), reject H_o. In this case $m = 8$ and $n = 7$. Tables for $w(\alpha, m, n)$ are provided in statistical reference works. Select $\alpha = 0.047 \approx 0.05$, so $w(0.047, 8, 7) = 71$. If $W \geq 71$, reject H_o. $W = 43.5 < w(0.047, 8, 7)$. This fails to reject H_o P-value > 0.5.

Recommendations

96. In terms of engineering interest, the number of felt events per unit time is the most unambiguous and meaningful measure of seismicity. Two recommended tests are the $2 \times 2\chi^2$ test and the two sample Wilcoxon. They are simple tests with few distributional restrictions.

Correlation Evidence

97. The term correlation is loosely used to indicate that two parameters are associated. In the study of induced seismicity the term correlation has been used to describe a general association between reservoirs and seismicity, and on some occasions the term has been used to imply a cause and effect relationship between reservoirs and seismicity. For the purpose of this report a correlation is a figure in which a reservoir variable and a seismic variable are plotted against one another or against a third reference variable, usually time. This is the prevalent definition used in the field of induced seismicity. In general usage (outside of this report) correlation data are presented in a variety of forms. They can be tabular, in a contingency table format, or graphical as a frequency surface or stereogram. In published studies of induced seismicity it is almost a universal practice to present a figure that has the reservoir variables and seismic variables plotted versus time. These correlations are used as evidence of a relationship between the reservoir and earthquakes.

98. In this section the assumptions underlying selection of data for correlation will be discussed in detail. In reservoir-induced seismicity the use of correlation data requires that a complex process of crustal adjustments to a massive fluid load be represented by a graphical

representation of two variables. Seismicity, water loading, and diffusion of fluid pressure each are five-variable parameters. This complex interaction must be reduced to two univariate parameters to perform a correlation. The use of two univariate parameters to model the more dimensionally complex process requires that information be discarded until the simple two univariate-parameter analysis is possible. If discarded information contains critical details of the processes that are not found in the two univariate parameters, then the correlation will not approximate the process. Even if all the critical elements are modelled, the discarding of information will mean that the correlation is at best only an approximation of the actual process.

Selection of variables for correlation

99. The variables correlated in reservoir-induced seismicity are a reservoir variable and a seismic variable. In this section both the correlation variables and complementary variables will be discussed. The relevance of these variables must be assessed with respect to a theory of induced seismicity. Theory is used to identify the relative importance of the variables.

Reservoir parameters

100. The selected reservoir parameter should represent the reservoir effects on stability and should increase with stress and with fluid pressure. Readily available choices are water level, reservoir volume, and stressed volume. The latter two correspond better than water level to the amount or volume of the crust being affected, but reflect magnitude of stress increase poorly. Stressed volume would correspond accurately if the crust behaved as a homogeneous elastic half space. As stated earlier, the theory of elasticity may only give a qualitative representation. Reservoir volume would also give similar qualitative information without using the required elastic assumptions or the required computer computation. Because of these drawbacks, stressed volume offers no decided advantages over reservoir volume and may be representative only if a simple crustal model is appropriate. Reservoir volume and water level are determined more readily. Water level, reservoir volume,

and stressed volume all will have the same turning points. Reservoir volume emphasizes the areal extent of the load, while water level records the intensity of the change in boundary load at a point. Both volume and water level are difficult to interpret in terms of a particular crustal volume. The use of any of the reservoir parameters requires a great deal of judgment. Water level is the most readily obtainable and is recommended as the reservoir parameter because of its accessibility and not for any seeming inferential advantage.

101. The most common set of variables selected is water depth and number of earthquakes per unit time. The following discussion will identify what the correlated variables represent and identify the range of the index variables.

Water level

102. The water level represents the elevation of the water surface. It is frequently referred to as a measure of water load. The water load is the weight of the volume of water impounded by the dam. The water level is sometimes equated to water pressure. Water level is shown in the correlation as an elevation that by itself has no clear meaning for either water load or pressure. Water load and pressure are related to water depth, which is the water level elevation minus the ground level elevation. The water level is a single value for the entire reservoir, but water depth varies from point to point over the reservoir basin. An increase in water level is identical to an increase in water depth for those points under water at the beginning of the increase. Similarly, the decrease in elevation is identical to the decrease in water depth for those points under water at the end of the decrease. For those points covered by water for less than the entire period the change is less than the change in water level.

103. Water load is poorly represented by water elevation. Consider the following example. Assume the reservoir is a prismatic solid, as shown in Figure 20. The valley walls slope at a grade of $1/S$ such that for a depth of water h, the reservoir is $2Sh$ wide at the dam. Let the valley gradient be $1/G$ so that for maximum water depth h, the reservoir is Gh long. The maximum depth is h and the average

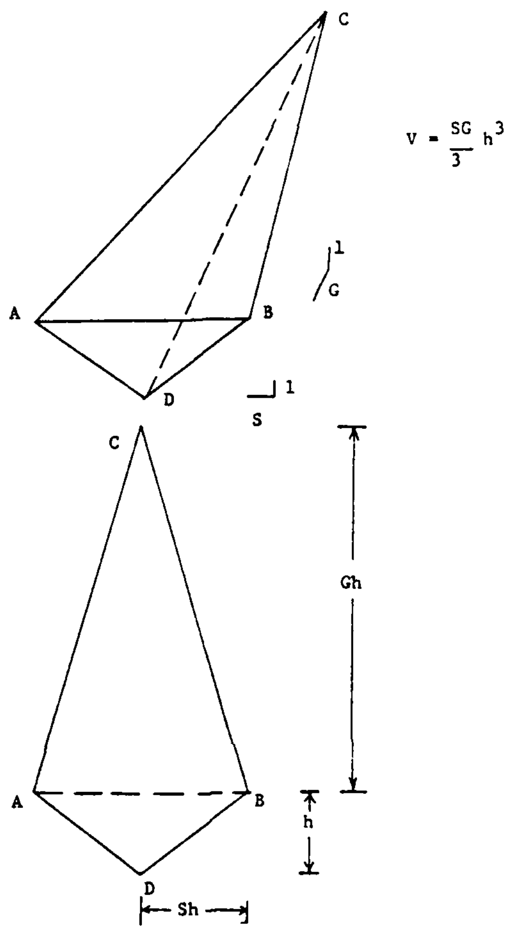


Figure 20. Prismatic reservoir

depth equals $h/3$. The volume equals $(SG/3)h^3$. The change in maximum depth scales linearly to the change in average depth and is related exponentially to the change in volume. A doubling of maximum water depth doubles the average water depth and increases the volume by a factor of eight. A halving of maximum water dept ı halves the average water depth and reduces the volume to one-eighth of its original value. As the reservoir level changes, the centroid of the load moves.

104. Actual data for Lake Mead and Lake Kariba are shown in Table 5. In the case of Kariba, average depths increase very slowly and erratically. A 10-m change in water level changes the average water depth from a negligible amount to as much as 5 m. An increase in depth

Table 5

Load and Pressure Changes Measured by Water Level

Elevation H	Height h	Δh	Pressure Increase $\frac{\Delta h}{h}$	Load (Volume) V	ΔV	Load Increase $\frac{\Delta V}{V}$	Depth h_{avg}
			Kariba*				
425	65		0.15	3.1		1.23	9
		10			3.8		
435	75		0.13	6.9		1.65	9.5
		10			11.4		
445	85		0.12	18.3		0.92	13.7
		10			16.8		
455	95		0.11	35.1		0.78	14.4
		10			27.5		
465	105		0.10	62.6		0.61	22.9
		10			38.1		
475	115		0.09	100.7		0.52	22.9
		10			51.9		
485	125			152.6			

Lake Mead**

Elevation H	Height h	Δh	Pressure Increase $\frac{\Delta h}{h}$	Load (Volume) V	ΔV	Load Increase $\frac{\Delta V}{V}$
800	100		1.00	1.32		2.61
		100			3.45	
900	200		0.50	4.77		1.30
		100			6.19	
1000	300		0.33	10.96		0.92
		100			10.06	
1100	400		0.25	21.02		0.71
		100			15.01	
1200	500			36.03		

* Data adapted from Gough and Gough (1970b); elevation and height are in metres and volume in km^3.

** Data adapted from Carder (1970); elevation and height in feet and volume represented by load in tons $\times 10^9$.

of 10 to 15 percent can increase load from 50 to about 150 percent. At Lake Mead an increase in water depth of 25 to 50 percent can increase load by 70 to 130 percent. Examination of water level plots does not readily provide accurate information on the increases in pressure or load. Water level data accurately identify the turning points of water load curve and accurately show the ordinal relationship of load versus time. The water level data show accurately the increase in pressure for selected locations that were under water over entire increases in water level.

Seismic variable

105. The occurrence of an earthquake depends on the strength of the crust. If the stress change due to the reservoir combines with the preimpoundment stress field to exceed the strength of the rock, an earthquake will occur. Whenever the stress is increasing or the strength is decreasing, an earthquake may be triggered. If the strength is not decreasing and the stress is not increasing, an earthquake should not be triggered. The size of the event is a function of the overstressed area of the fault plane and the amount of slip. Whether one large event takes place or several smaller events depends on the homogeneity of the stability of the fault plane. This means the size of the event should be governed by properties of failure planes as well as stress change caused by the reservoir. The size of events rarely is directly used in correlation data. The log of the energy release is used more frequently as a variable. The principal difficulty with the incorporation of size is the observation that one moderate earthquake may contain the energy equivalent of several hundred smaller events.

106. An additional difficulty is the aftershock phenomena. When a moderate event occurs ($m_b \geq 4$), the fault zone may produce aftershocks that may be the result of stress redistribution due to the main event. The persistence of aftershocks may distort the seismic data. The most frequently used seismic variable in correlation data is the number of events occurring during some specific time period. The shortcomings of this variable were discussed in detail in Part II. Despite its

deficiencies, the number of events remains the most reasonable seismic variable to use in a correlation.

Number of earth-
quakes per unit time

107. The number of events per unit time requires that the values of the seismicity parameter be grouped over a selected time interval. The selection of the length of a time interval affects the appearance of the plot. The time interval selected by various researchers varies from one day to three months. The grouping of the data in this manner simplifies the presentation but discards information regarding time-varying behavior within the time interval. As an example, Hagiwara and Ohtake (1972) presented the seismicity data as events per month. The average number of events per month was about 14. If events per day were plotted, more than one-half of the data points would be zero. With the monthly grouping, 4 of the 83 data points were zero. The number of events per half day would present a different picture. In Figure 21, the frequency distribution of shocks is plotted against solar time. Events occurred more often at night (12-24 hr) than during the early portion of the day (0-12 hr). By grouping the data by month, this behavior as well as all other daily and weekly behavior is lost.

108. Another grouping occurs in the size parameter. Not all events are detected. There is some threshold magnitude above which all events are recorded. A change in threshold magnitude has a pronounced effect on the data. This is shown in the data of Rogers and Lee (1976). Figure 22 shows the data with a threshold magnitude of $M_L = 1.5$ and a threshold magnitude of $M_L = 1.0$. The location variables (x, y, and z) are bounded due to the detection capability of the seismic network.

109. In some cases the range of locations is specified by counting only those events with an S-P time less than some arbitrary criterion. This provides a fixed boundary of location parameters over the entire data set.

110. In some cases the instrument array or net is composed of portable instruments, which are moved during the data gathering to optimize the accuracy for determination of hypocentral parameters. This may

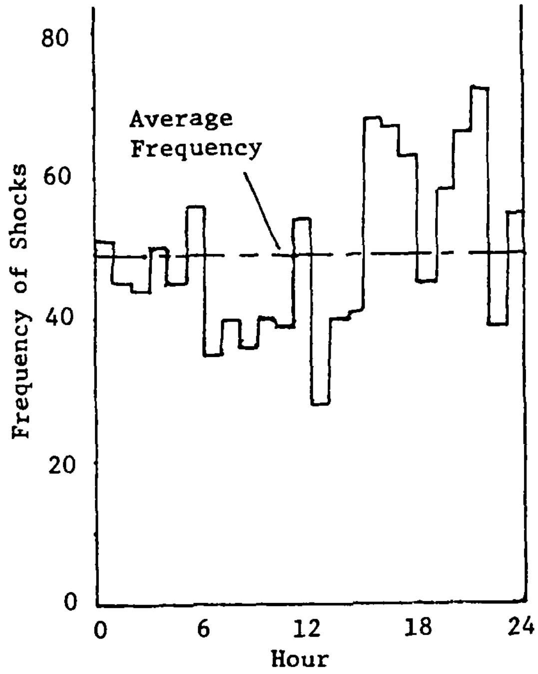


Figure 21. Histogram of damsite shocks at Kurobe (after Hagiwara and Ohtake (1972))

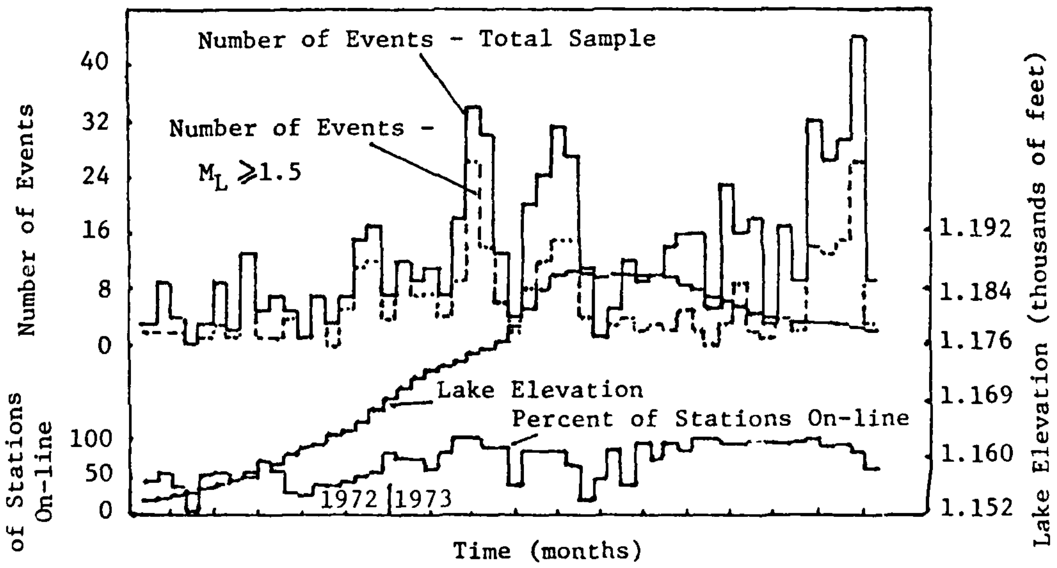


Figure 22. Correlation data, Lake Mead, 1972-1973 (after Rogers and Lee (1976))

change the location boundaries. Detection boundaries are also a function of the magnitude of events and instrument characteristics. The ease of interpretation of the correlation rests on the similarity of the complementary variables.

111. If both the reservoir variable and the seismic variable had identically valued complementary variables, the interpretation of the correlation would be more certain. An example from the work of Mogi (1962) may illustrate this point. Crystalline rock specimens were prepared as beams and subjected to bending stress. As the applied load on the specimens was increased, microfractures took place. The microfractures were recorded using an acoustic method. The number of shocks per unit time was the fracturing parameter used. The selected time interval was 5 sec (Figure 23). Stress was plotted versus number of shocks per 5 sec. Several other time intervals were used by Mogi in presenting his data.

112. In this laboratory situation the load variable is known and can be expressed in terms of load intensity l , time t , and points of application (spatial coordinates) x , y , and z . The load variable is completely described as a five-parameter variable $L\ (l, t, x, y, z)$. The distribution of stress through the specimen can also be calculated. The fracturing can be described as though it were an earthquake. The occurrence of a fracture can be specified by the size, time, and location of the event. The location coordinates are limited to the ranges that describe the sample dimensions. Mogi plotted number of shocks per 5 sec versus load intensity l . The number of shocks is a simple count of shocks that treats all size shocks as equal. Time is shown indirectly through both correlated variables. For an individual data point in Figure 23, the time parameter is the same for both variables. Mogi also plotted energy release versus load intensity (not shown in Figure 23). In the laboratory, it is known what the applied load is and how it is distributed and that no other loads are operating on the specimen.

113. Unlike the laboratory setting, in the field several important factors are unknown. In reservoir-induced seismicity the ranges of the complementary variables are more difficult, if not impossible, to

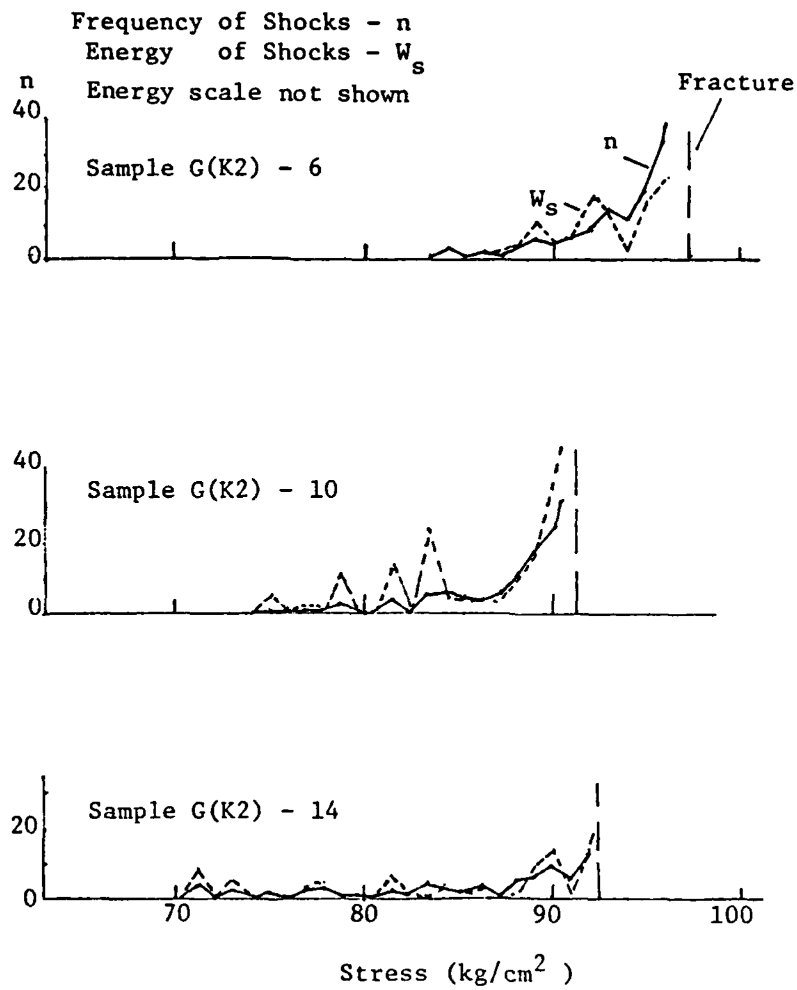


Figure 23. Frequency and energy versus stress (after Mogi (1962))

describe. The complementary load variables are, in principle, known and could be expressed quantitatively. The complementary variables of seismicity are not as well defined. Magnitude is neglected and the location variables are known for only a fraction of the data points. The most limiting hardship in the field case is that it is known that other loads are present but little is known of their distribution and magnitude. The reservoir loading is known, but is is uncertain how the crust adjusts to the loading. This limits the usefulness of the correlation in ways that cannot be estimated. Still, if the uncontrolled factors do not change with time (or change very slowly with time) this correlation technique may be used profitably.

114. The correlation is applicable to those situations in which the complementary variables are similar to those for which the correlation is developed. This point is critical. The values of the complementary variables determine the limits of applicability of the correlation. An example where these variables are compared is found in the discussion of the correlation evidence presented for Kremasta Reservoir. The important variables should be identified with the aid of a model of induced seismicity. A theory of triggering will describe the role of the reservoir in triggering release of tectonic stress.

Triggering process

115. Earthquakes are the result of sudden brittle slippages in the crust. The reservoir impoundment can contribute to the slippage by adding a load to the crust, by reducing the strength of the rock mass by increasing fluid pressure, or both. At depths greater than a few hundred metres the stress due to the loads makes up a small fraction of the ambient stress. Because of this small role, the balance of the other stresses must be responsible for bringing the rock mass close to failure. If the rock mass is not close to failure, then the reservoir cannot cause failure. The reservoir acts only as a trigger to trip off an impending earthquake.

116. At very shallow depths (<1000 m) high vertical tectonic stress cannot be sustained because of the ability of the near-surface material to achieve stress relaxation by movement of the free surface. At very shallow depths the stress field due to the reservoir constitutes a larger portion of the complete stress field (ambient plus induced) than at greater depths. Stress changes may result if the temperature of the rock mass were modified by the reservoir. It is conceivable that such stress changes could cause microearthquakes. Microearthquakes ($M < 3$) and ultramicroearthquakes ($M < 0$) generated in this zone may be unrelated to tectonism and do not represent triggered release of tectonic stress. In this report induced seismicity applies to release of tectonic

stress in the form of macroearthquakes and does not apply to microseismic events generated by surface activity.

Strength of the rock mass

117. The rock mass is assumed to have frictional strength. This strength on any plane is proportional to the normal stress across that plane multiplied by the coefficient of friction. When the applied shear stress on a plane exceeds the strength, failure occurs. The rock is assumed to have numerous fractures. Failure will take place on an existing fracture rather than through intact rock (rock elements). The rock strength is governed by the normal stress on a potential failure plane.

118. The rock mass is considered a two-phase medium in which the rock mass is saturated and fluid is present between all blocks of intact rock. The rock mass strength is governed by effective stress; rock element (intact rock) strength is governed by total stress. Earthquakes are large-scale phenomena which involve the rock mass. Engineering projects (tunnels, dams, foundations) involve a much smaller scale. In certain circumstances the stability of engineering structures may be governed by the stability of large rock elements that can be designed on the basis of total stress. Crustal mechanics (overthrust faulting, earthquakes) involve stress changes affecting many cubic kilometres of material whose stability is governed by the effective stress. The interparticle stress and fluid pressure are the stresses acting on potential failure planes. The fluid pressure acts to separate the blocks and reduces the interparticle stress. Within the blocks there is only a solid phase. The stress in the solid phase can be determined from elastic theory. The interparticle stress must equal the solid phase stress (usually called total stress) minus the fluid pressure. The interparticle stress is often called the effective stress because it governs the frictional strength of the rock mass.

119. The forces within the fluid do not change instantaneously as in linear elastic solids. The changes of pressure in the fluid are time-dependent. The nature of the fluid behavior must be well understood to provide insight into the stress-strength caused by reservoirs.

Fluid forces

120. The Bernoulli equation describes the nature of fluid flow. The expression is

$$\frac{p}{\gamma_w} + Z + \frac{v^2}{2g} = \text{Constant}$$

The first term, p/γ_w , is called the pressure head. The second term, Z , is called the elevation head. The third term, $v^2/2g$, is called the velocity head. The sum of the first two terms is called the piezometric head, h ; thus the equation can be rewritten

$$h + \frac{v^2}{2g} = \text{Constant}$$

The slope of the piezometric head is called J . The value of J is also known as the gradient i . Darcy empirically related the seepage velocity, v , to i in the form $v = ki$, known as Darcy's law.

121. The constant k is the coefficient of permeability. Examination of these equations will show that i is dimensionless and therefore k must have units of velocity. This value k also is known as the seepage coefficient. The seepage coefficient is not a fluid property or a property of the solid matrix in which the fluid flows. It contains elements of both and can be expressed as $k = k_o g/\nu$ where k_o , which is a property of the solid matrix, has units of area and ν , which is the kinematic viscosity, has units of area per time. Within the rock mass, k and the velocity are usually low. The velocity head in the Bernoulli equation is very small compared to the piezometric head. When the fluid flows, a seepage force is created in the direction of flow equal to $i\gamma_w$. The fluid pressure p is the value that must be subtracted from the total stress to yield effective stress. The evaluation of fluid pressure is uncertain. Consider the situation illustrated in Figure 24. Fluid pressure within the pores of a solid matrix can be changed in three ways. One way is by a change in boundary fluid pressure. A second way is by a change in pore volume due to loading of the solid matrix. A third way is by a direct change in fluid pressure within the pores due to pumping. If the change in total head is not uniform, fluid flow will begin. If the velocity head can be neglected and the

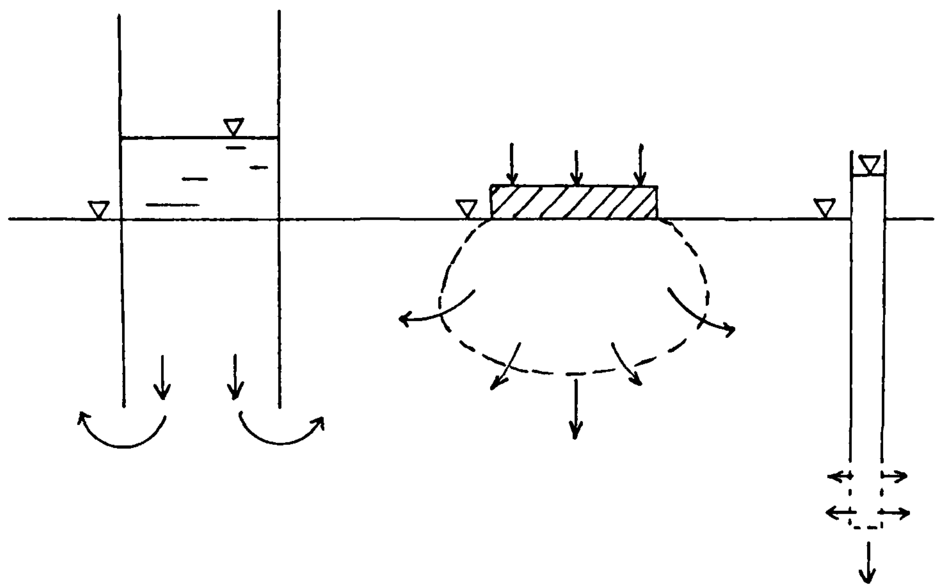
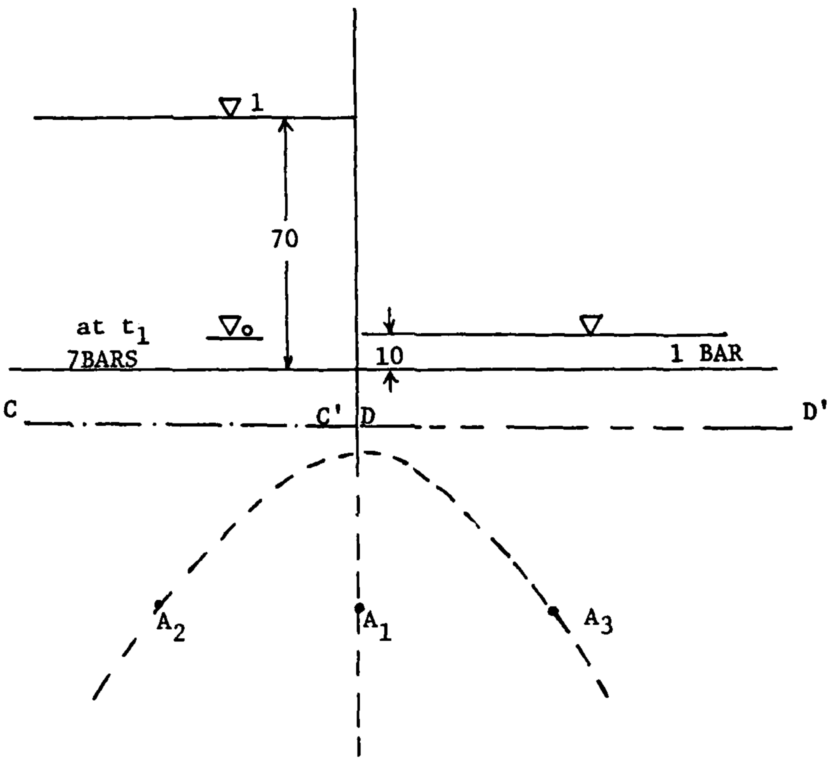


Figure 24. Three ways fluid pressure can be changed

elevation remains constant, the change in total head is equal to the change in pressure head. Consider the condition illustrated in Figure 25. At $t = 0$ the fluid level is the same on both sides of the sheet pile. At $t = t_o$ the water level on the left of the sheet pile is increased by height d. Immediately there is an increase in total stress at any point B of $C_1 \gamma wd$. If the media is permeable and the water levels remain constant, a steady-state flow will result. At some time t the water pressure at point B will equal $C_2 \gamma wd$. The change in vertical effective stress will equal $(C_1 - C_2)\gamma wd$. If an impermeable layer existed at $C - C'$, the change in effective stress would equal $C_1 \gamma wd$. If an impermeable layer existed at $D - D'$, the change in effective stress would equal zero. C_1 is dependent on the location and Poisson's ratio. The constant C_2 is a function of location and the geometry of the flow net and location of impermeable barriers, if any. The change in water level d is a scale factor. The simplicity of the expression is achieved because a two-dimensional analysis is used



$\gamma_w = 10^3$ Kg/m^3

$\gamma_R = 2.7 \times 10^3$ Kg/m^3

A_1 , A_2 , A_3 are at a depth of 50m

at t_o water depth is 10m

at t_1 water depth is 70m

Figure 25. Example of effective stress change

and the change in vertical effective stress is the selected parameter of interest. The change in vertical stress may be a poor indicator of stability. This is particularly true when the vertical stress is not the major principal stress. In the example in Figure 25 at point A_1 , C_1 equals C_2 and both equal one-half. At point A_2 the increase in total stress is greater than at A_1 and the change in total stress at A_3 is less than that at A_1 . The existence of impermeable barriers at either C - C' or D - D' requires that the fluid pressure at each of these points be equal. Since the details of the permeability of the crust at depth are unknown in almost all cases the most reasonable approach is to bound the problem. So for point A_1 the change in effective vertical stress ranges from zero kg/m^2 to $+3 \times 10^4 kg/m^2$. This bounding approach is limited because this range is applicable only to an elastic half-space with uniform mechanical and hydraulic properties.

122. Fluid pressure changes accompanied by volume change are time-dependent and the fluid pressure adjusts to seek equilibrium under the boundary conditions. The rate of change is a function of the diffusivity of the porous media. Given a change in boundary condition the fluid will change to adjust to the new boundary condition. As a further complication the reservoir boundary conditions also change as a function of time. This makes the estimate of pore pressure changes particularly difficult. In many cases of induced seismicity there is time lag observed from the time of a change in load to the observed change in seismicity. This time lag is often held to be the time required for a change in pore pressure. The process of pore pressure change must be clearly understood to evaluate effective stress. A change in fluid pressure can be due to a change in volume of the pores in the porous media. A time lag is present only when there is a change in mass per unit volume. This lag occurs because a net change in fluid volume must occur in the unit volume for the change in mass to take place. The rate of change in volume is controlled by the permeability of the porous media. The consolidation of saturated soils is an example.

123. The soil consists of a skeleton made up of soil particles and void space (pores) between particles. The pore volume is filled

with water. The individual soil particles and the water are both relatively incompressible compared to the skeleton. When the saturated soil is loaded, the pore volume of the skeleton will be reduced as the soil particles shift and rotate under the load. This reduction in pore volume is reached primarily through fluid flow and, in part, through compression of the water and soil particles. During compression the pore fluid pressure is increased. The increase in fluid pressure sets up a gradient and flow begins to regions of lower total head. The flow is governed by Darcy's law. The velocity is a function of permeability and gradient. The gradient is time-dependent because as fluid leaves the pores, the pore volume decreases and the solid matrix approaches equilibrium; no further pore volume change is required and the gradient vanishes. The link between the fluid pressure and the solid matrix stress is the pore volume. A change in fluid pressure requires a change in pore volume, and similarly a change in pore volume requires fluid flow, which takes time and is the source of the time lag. The change in volume is due to a change in load. Load-induced pore pressure changes occur immediately and dissipate gradually. There is no time lag in the increase or decrease of fluid pressure in response to the load. If the change in load occurs slowly enough to permit the flow, the pore pressure will rise only enough to initiate flow.

124. When a change in head occurs at a boundary, there is a change in gradient immediately. There is a change in the pressure head within the pore fluid. If an increase in fluid pressure occurs, the pore volume will increase. The rate of increase in pore volume is controlled by the permeability. The change in pore volume is a function of the change in the effective stress and modulus of the solid matrix. Instantaneous volume change is never experienced. Whenever the pore volume is saturated with a liquid, the instantaneous volume change is zero. The liquid assumes a pressure that will compensate for the change in mean total stress such that there is no change in mean effective stress. There will be some distortion of the pores but no volume change. The distortion is brought about by a change in shear stress. The change in shear stress is a function of the Poisson ratio of the solid matrix and the distribution

of the boundary load. The change in pore pressure is less than the change in vertical effective stress in cases of changing load unless no lateral strain is permitted in which case the change in pore pressure equals the change in load (one-dimensional consolidation). Within most materials, time lag is significant only in dissipation of load-induced excess pore pressure.

125. In low porosity materials such as crystalline rock, time lag is significant when head change occurs at a boundary. The change in head causes a change in fluid pressure within the medium. The change in pressure causes a change in volume. The volume change requires flow to achieve the change. The flow rate is determined by the permeability and gradient. The time-dependent change in rock has been observed at damsites.

Stability criteria

126. Parameters designed to evaluate the effects of reservoir impoundment on stability of the rock mass are called stability criteria. Stability criteria relate stress changes caused by impoundment to stress changes that could lead to failure. The specific failure mode commonly used is slippage along a fault plane. Failure occurs when shear stress on a plane exceeds the shear strength on that plane. Failure need not occur on the plane where the shear stress is maximum if there is sufficient shear strength on that plane. In fact, the failure plane is never the plane of maximum shear stress. This is shown in Figure 26. The figure is a Mohr circle representation of the stress on the principal plane. The Mohr-Coulomb failure line is shown. Failure will occur on a plane inclined at an angle of 45 deg + $\phi/2$ to the major principal plane. Phi, ϕ , is the angle of internal friction. The coefficient of friction is equal to tan ϕ . If the rock mass has negligible cohesive strength, then the strength is described completely by ϕ . At failure the ratio of the major principal stress to the minor principal stress, σ_1/σ_3 , equals $\tan^2(45 + \phi/2)$. In materials with cohesive strength, C , the relationship must be modified to $(\sigma_1 + C)/(\sigma_3 + C)$. It is attractive to neglect cohesive strength by rationalizing that the rock is fractured and the cohesive strength across the fractures is zero. However, if a

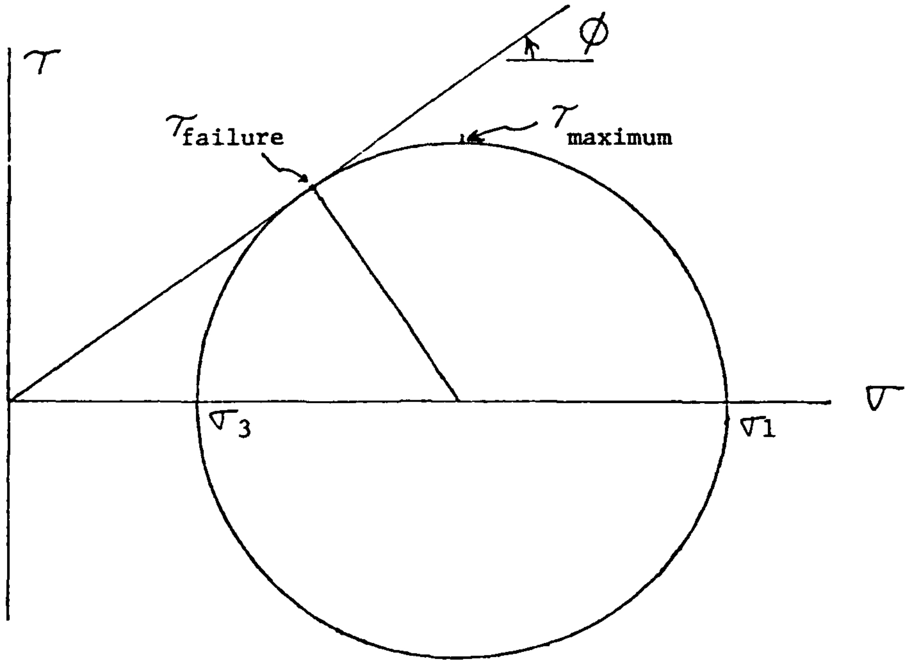


Figure 26. Stress at a point at failure

material has no cohesive strength, it can withstand no tension.

127. Consider a half-space with a boundary load. The deflection pattern may be visualized by having the surface stretched and the material beneath the load compressed. If the material had no tensile strength, it must fail at the surface. The failure occurs but it is not catastrophic because only a small portion of the material is faile and the failure may not propagate. Felt earthquakes involve failure of material over a fault plane whose area is at least several square kilometres. Because local tensile failures are not important, stability criteria sensitive to local failures are not useful.

128. Another criteria is deviatoric stress or shear stress. Although the maximum shear stress is not the shear stress of the failure plane at failure, it is proportional to the shear stress on the failure plane. The maximum shear stress is equal to one-half the difference of the major and minor principal stress.

129. Withers and Nyland (1978) use the following argument to

develop a stability criterion. The reservoir load is small compared to the tectonic stresses. The stress field of interest is the field composed of the tectonic stresses and the reservoir-induced stresses. Since the tectonic stresses constitute such an overwhelming portion of the composite stress field, the principal stress directions of the composite stress are almost identical with those in the tectonic stress field. The principal stress directions in the tectonic stress field are assumed to be representative of the fault type present in the region. A description of principal stress orientation by fault type is shown in Figure 27. In all cases it is assumed that the vertical and horizontal axes are the principal stress axes. The vertical axis is labelled the z axis and horizontal axes correspond to the x and y axes. Withers and Nyland used the normal stresses in the x, y, and z planes to construct a stability criteria. From the fault type, they selected the pair of normal stresses that correspond to the major and minor principal stress. These are combined to compute the normal stress defining the center of the largest Mohr circle $(\sigma_1 + \sigma_3)/2$ and maximum shear $(\sigma_1 - \sigma_3)/2$. For example, in the case of normal faulting σ_1 is σ_v and σ_3 is σ_H. So σ_1 is taken as σ_z and σ_3 as σ_x. Note that the model is two-dimensional and σ_y is always assumed to be the σ_2. So $(\sigma_x + \sigma_z)/2$ and $(\sigma_z - \sigma_x)/2$ are calculated. These two parameters define the center and radius, respectively, of a Mohr circle. The effective stresses are determined by subtracting the fluid pressure from the mean total stress. The fluid pressure is calculated using a consolidation model adapted from Biot (1941). Instability is measured graphically as the locus of a point on a line inclined at 30 degrees to the normal stress axis and tangent to the effective stress circle.

130. Bell and Nur (1978) use a stability criterion they label incremental strength, ΔS. The incremental strength is formulated as $\Delta S = g\ (\Delta\sigma - \Delta P_p) \pm \Delta T$ where $\Delta\sigma$ and ΔT are the incremental normal and shear stress on a plane due to the water load, respectively, g is the coefficient of friction, P_p is the incremental pore pressure induced by the water load. The decision to add or subtract ΔT depends on the faulting type. The shear is added to normal faults, subtracted

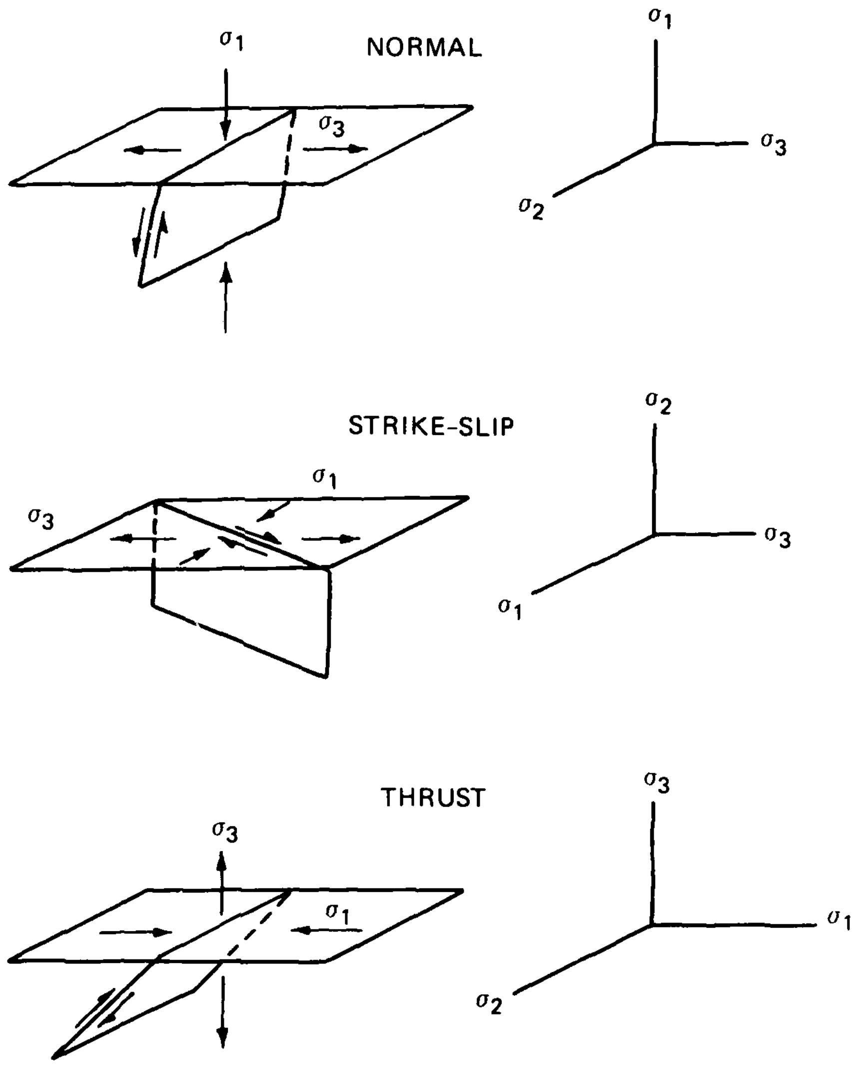


Figure 27. Assumed stress orientation based on fault type

from thrust faults, and ΔT is zero for strike-slip faults. A model adopted from Rice and Cleary (1976) is used to calculate pore pressure increase and dissipation. In their model, variations in permeability are accommodated.

131. Snow (1972) used a stability criterion based on the assumption that the rock mass has only friction strength and is at failure prior to reservoir impoundment. The ratio $\Delta\sigma_3/\Delta\sigma_1$ is used as a stability criterion. The ratio $\Delta\sigma_3/\Delta\sigma_1 = (1 - \sin \phi)/(1 + \sin \phi)$ where ϕ is the friction angle. Snow uses a model of an infinite reservoir to calculate changes in fluid pressure. The stability parameter is calculated in terms of effective stress. Selection of the major and minor principal stress is dependent on fault type. Since the model uses an infinite reservoir, the change in stress as measured by the stress change ratio is independent of location within the crust.

132. The three stability criteria presented above each require calculation of effective stress. Each method uses a different model to determine total stress and pore pressure. Once these quantities are determined, effective stress is calculated by substracting the pore pressure from the total stress.

133. Each model has drawbacks. The model used by Snow assumes that the reservoir has infinite lateral dimensions. This assumption is unrealistic. Both of the other models are consolidation models. Pore pressure calculations in these two models depend in part on assumptions regarding pore pressure at the surface of the crust.

134. Coupling is the expression that describes the continuity of fluid pressure from the bottom of the reservoir into the surface of the crust. Zero coupling exists if the reservoir water were replaced by an equivalent weight of ice (or other solid). One hundred percent coupling exists if the fluid pressure gradient was smoothly continuous from the bottom of the reservoir into the surface of the crust.

135. Withers (1977) conducted an analysis using a variety of coupling values. Bell and Nur (1978) used both zero coupling and 100 percent coupling. They refer to this as the case of the impermeable reservoir (zero coupling) and the permeable reservoir (unity coupling).

Bell and Nur used a compressible fluid model in which the relationship between the mean total stress and the load-induced pore pressure is called the pore pressure-stress coupling. This term has no direct relationship to the term coupling discussed above.

136. The assumptions regarding fluid compressibility significantly influence the stability analysis. Withers (1977) used an incompressible fluid model, but he investigated the effects of permitting fluid compressibility. He noted that the conclusions can vary considerably based on the selection of fluid parameters. Bell and Nur who used a compressible fluid model, commented that uncertainty in the compressibility parameter (which they call coupling), in situ permeability, and magnitude and orientation of tectonic stress are major limitations in their analysis.

137. The use of a stability criterion as the reservoir parameter in a correlation has the advantage of translating the reservoir impoundment into a quantity that may be readily interpreted but has the disadvantage of incorporating large uncertainty into the correlation because effective stress in the crust cannot be confidently predicted.

138. Up to this point several stability criteria have been discussed. All are based on effective stress and all apply to stress at a point. Recall that local failure in the rock mass is not important unless the failure propagates to involve a large fault plane or volume of material. Ideally, it is important to determine how much material is at a particular level of instability. This could be approached by determining the areas within contours of instability. In turn, this might be plotted versus a common reservoir variable like water level and used to interpret correlation data. One attempt at describing the spatial aspect of reservoir-induced instability was the use of stressed volume as a reservoir variable. Gough and Gough (1970a) calculated stressed volume for Kariba. The stressed volume was described as that volume of the crust that had a reservoir-induced shear stress greater than one bar. This volume was estimated using elastic theory, which is likely to be appropriate only if the crust is very uniform.

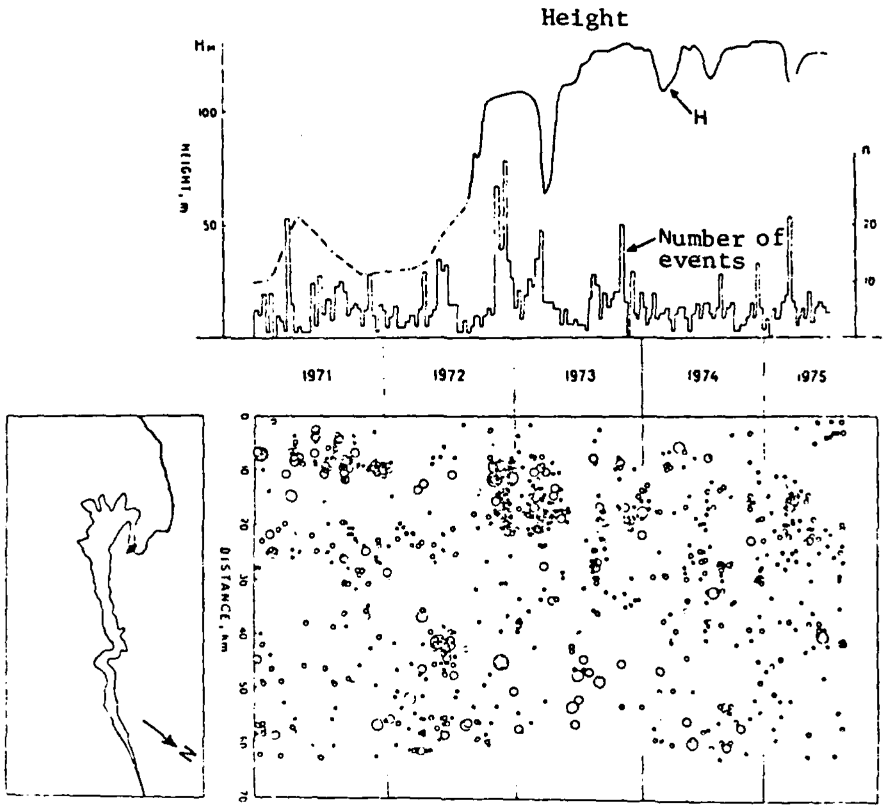
Spatial relationships

139. The location parameters of both the reservoir and seismicity variables usually are not treated in a formal fashion as correlation data. The location parameter of the seismicity variables often are restricted to a given range within which the reservoir may have influence.

140. Earthquakes often cluster in space. The region defined by a cluster may be considered an earthquake source. Since reservoirs are postulated to trigger earthquakes rather than to create earthquakes, likely sources of induced events are sources previously identified by historical or geologic evidence. It seems that active faults located in or near reservoirs should be likely locations of induced seismicity, but the mere existence of such faults does not imply that induced seismicity will result automatically from reservoir impoundment. Reservoirs located near active faults are discussed by Sherard, Cluff, and Allen (1974). None of these reservoirs has been associated with induced seismicity.

141. Let an active fault be defined as a fault capable of producing macroseismicity. In those cases where active faults have not been identified prior to impoundment, induced macroseismicity should cluster about active faults. In the absence of active faults, can induced events occur? This is a moot point in terms of engineering. If macroearthquakes cannot be triggered, then the presence of the induced macroearthquakes is not threatening.

142. The location of groups of earthquakes has appeared to migrate in most cases. The term migration implies that all the events are related. Groups of unrelated events could be construed to migrate as well. In many cases the location of events is recorded and discussed but rarely is treated in correlation data. At Nurek, epicenters are shown in a plot that also contained water level and number of earthquakes per 10 days (Figure 28). In the case of Kariba, Gough and Gough (1970b) treated clusters of events by estimating the change in stress at the locations of the groups and then postulating the influence of the reservoir on the occurrence. They did not treat the groups separately as correlation data.



Circles represent epicenters

Figure 28. Correlation data, Nurek Dam
(after Soboleva and Mamadaliev (1976))

Statistical treatment

143. The correlated variables are required to be sets of independent observations. If these observations come from a process in which the fundamental character of the specimen changes during the treatment, the process is not amenable to classical correlation methods. In mechanical terms the system is inelastic and the inelastic parameters depend on time and on the history of the process. In inelastic processes the sets of correlated variables are not independent but are dependent on the previous values assumed by the variables. Each variable is a time series rather than a string of independent values. A time series requires different techniques from analysis of the correlation data made up of sets of independent pairs.

Recommendations

144. The preparation of correlation data should be done in a manner that will provide the most inferential power. Even the most optimally selected parameters will fall short of providing proof of induced seismicity. Consider the possibility that an earthquake could take place naturally at a location of a reservoir. If this occurred, could it be proved that the event was unrelated to the reservoir? Since the state of the art is such that events cannot be predicted with confidence, it is impossible to prove or disprove a relationship between the reservoir and the earthquake. In spite of this shortcoming, there is a consensus on what causes an earthquake. Earthquakes are caused by sudden brittle failure in the crust. The crust is believed to be composed of a fractured rock mass whose strength is primarily frictional. Additionally, it is assumed that the effects of the reservoir on stress and strength of the rock mass at least can be described qualitatively. With the use of these assumptions, a theory of triggering can be formulated and the important factors identified. Current theories of triggering have been discussed previously. What follows is a statement of recommended theory, identification of critical variables, construction of a correlation, and interpretation of the correlation.

Triggering assumptions

145. The rock mass is composed of fractured rock whose strength is frictional and controlled by effective stress. The rock mass is not assumed to have uniform mechanical or hydraulic properties. Earthquakes occur as slippages on fault planes when the shear stress on a plane exceeds the shear strength on that plane. The reservoir impoundment produces changes in effective stress that cannot be portrayed with confidence in quantitative terms.

Critical variables

146. The correlated variables consist of a reservoir parameter, water level, and a seismic parameter, time rate of earthquake occurrence. These two parameters were selected because they are easy to acquire and they are raw data that are free from assumptions concerning the rock mass and characteristics of seismicity.

147. The interpretation of the correlation must rest on assumptions concerning the triggering process. Restrictive assumptions should be avoided.

148. A stability criterion is required to convert the reservoir parameter into a variable that can be interpreted using the theory of triggering. Previously discussed stability criteria depend on simple crustal models. A more general approach is recommended. Failure (slippage) will occur when shear stress on a fault plane exceeds shear strength. During impoundment the shear stress on a fault may change or remain constant. The shear strength on this fault may change or remain constant. During impoundment the shear stress and shear strength on a fault plane can respond in one of the nine ways shown in Figure 29.

STRESS	INCREASE	NO CHANGE	DECREASE
STRENGTH			
INCREASE	T	N	N
NO CHANGE	T	N	N
DECREASE	T	T	T

DURING STABILITY STATE T TRIGGERED EVENTS ARE POSSIBLE

DURING STABILITY STATE N TRIGGERED EVENTS ARE NOT POSSIBLE

Figure 29. Stability states

These nine ways can be separated into two sets, those where triggering is possible and those where triggering is not possible. The set where triggering is possible is called stability state T and the set where triggering is impossible is called stability state N .

149. The reservoir parameter and the seismic parameter must be interpreted through the stability conditions. The information necessary to permit this interpretation are critical variables. Identification of some of the critical variables is possible by reviewing the sheet pile example shown in Figure 25.

150. In that problem the change in vertical effective stress due to a rise in the water level was evaluated. The change in vertical total stress was dependent on (a) the magnitude of the water level change and (b) the location of the point where the stress change was evaluated. Shear stress was not evaluated in that example. The additional information required to evaluate the change in shear stress is (a) principal stress orientation and magnitude and (b) fault plane orientation and elastic constants of the rock mass.

151. In that problem the change in pore pressure due to the changing fluid pressure at a boundary was evaluated. The change in pore pressure depended on (a) the magnitude of the water level change, (b) the location of the point at which the pore pressure was evaluated, and (c) the influence of hydraulic barriers. The load-induced pore pressure changes were ignored. The evaluation of load-induced pore pressure changes requires the following additional information: (a) time rate of loading, (b) permeability of the rock mass, and (c) empirical relationship to evaluate pore-pressure change due to change in mean normal total stress and pore-pressure change due to dilatant characteristics of the rock mass.

152. The critical variables are restated and paraphrased as: (a) location of evaluated point, (b) magnitude of water level change, (c) hydraulic conditions, (d) principal stresses, (e) fault orientation, (f) constitutive relations (elastic and empirical constants), and (g) time.

153. Some of the critical variables (a, b, and g) are considered during construction of the correlation. All of the critical variables are considered during interpretation.

Construction of the correlation

154. The correlation should be constructed by plotting the water level, and the rate of earthquake occurrence on the ordinate and time is plotted on the abscissa. This type of plot is almost universal in reservoir-induced seismicity literature. The water level shows qualitatively the magnitude of the load and boundary pore pressure change and the rate of this change.

155. The rate of earthquake occurrence is the number of events detected in a certain time period. This seismicity parameter is a collection of individual earthquake occurrences. The data base for the seismicity parameter should be edited using earthquake size and location criteria. The minimum size should be high enough to screen out nontectonic events. A magnitude of 2 is recommended. The events should be grouped by a location criterion. Natural groupings may be suggested if spatial clustering is observed. If the seismicity is diffuse, the data should only include shocks detected within the area of influence of the reservoir. If groups are created based on spatial criteria, each group should be plotted as a separate seismic variable. Grouping by location will assist interpretation of the correlation.

Interpretation

156. The interpretation of the correlation has as a goal the identification of the observed seismicity into two groups--a group that may have been triggered and a group that could not have been triggered. All of the previously listed critical variables must be addressed to achieve the stated goal. If some of the critical information is missing, the interpretation becomes less certain. Some of the critical information will always be missing because its discovery is beyond the state of the art. Examples of this type of information are (a) site hydrologic conditions, (b) constitutive relations for the rock mass, and (c) principal stress magnitude and orientation. Since this critical information is missing, interpretation of correlation evidence is speculative. Assumptions concerning the missing critical information must be made to permit any reasonable interpretation. The assumptions that follow permit an interpretation to be made, but it is recognized that such assumptions make the interpretation a matter of opinion:

a. The principal stresses are assumed to be oriented consistent with the predominant fault type at the reservoir site.

b. The principal stresses are assumed to have magnitudes that are large enough that rock mass is near failure.

c. The rock mass has permeability such that load-induced pore pressures (excess pore pressure) are dissipated within 1 year after loading becomes constant.

157. In soils, dissipation of excess pore pressure may take several years. In some clay shales a dozen years may be required but it is assumed that the rock mass is fractured and the fluid flow occurs along preferred directions due to the fracturing. The tectonic events large enough to cause damage are assumed to occur in fractured crystalline rock at depths of 5 km or more. In this material it is assumed that excess pore pressure will dissipate in 1 year. The assumptions are summarized below:

a. Hydraulic conditions will be addressed by assuming two extreme conditions. One condition is a reservoir with a pervious bottom that would have fluid communication with the crust. This condition describes a fluid pressure gradient that is smoothly continuous from the reservoir bottom into the crust. The other condition is the impervious reservoir where the fluid pressure gradient from the reservoir bottom into the crust is discontinuous. Outside of the reservoir the groundwater table remains at the preimpoundment level. In the case of fluid communication the groundwater table eventually rises to the reservoir water elevation. It is assumed that the change in groundwater elevation lags the change in reservoir level by 2 to 3 years.

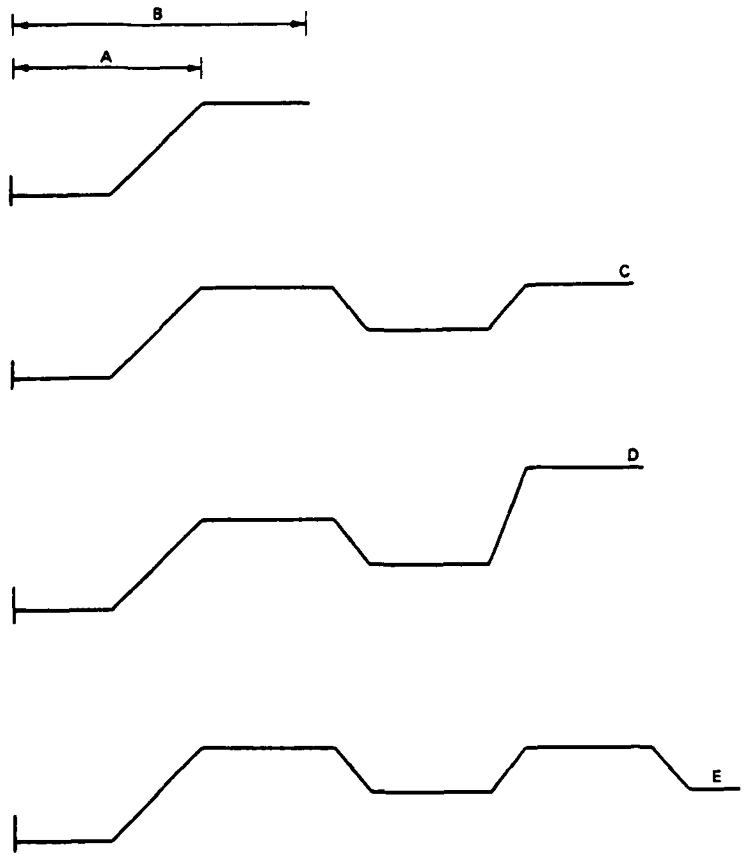
b. The change in total vertical stress is more easily estimated from water level than change in shear stress. It is assumed that the appearance of the water level curve can be used to make an intuitive estimate of the change in total vertical stress ($\Delta\sigma_v$) for a location within or around a reservoir.

c. It is assumed that the appearance of the water level curve can be used to make an intuitive estimate of the change in pore pressure (Δp) for a location based on assuming a condition of fluid communication or no fluid communication.

158. After a plot of $\Delta\sigma_v$ and Δp are prepared for a location, the stability condition, T or N, is estimated. The seismicity observed for the location is compared to the stability state. If the seismicity is triggered, the events should occur during stability state T. Seismicity observed during stability state N is assumed to be natural. A comparison of natural events with those that possibly are triggered can provide an opinion concerning the role of the reservoir as the source of induced seismicity. Amplification of this interpretation technique is presented below.

159. Most maximum reservoir loadings are achieved within 2 to 3 years of beginning of impoundment. After maximum loading is achieved, the reservoir will seasonally cycle or remain relatively constant based on operational policy and weather. During the first filling, the crust is subjected to increasing loads and fluctuating pore pressures. A number of typical loading patterns are shown in Figure 30. The figure has no scale. The changes in the parameters $\Delta\sigma v$ and Δp are incremental changes for a location beneath the reservoir due to the applied load as shown in Figures 31 to 34. The five loading patterns cover the most common types of reservoir operation. In terms of water levels all loading patterns are composed of periods where the applied load increases, decreases, or is stationary. The total stresses under the reservoir increase as water level increases, remain constant when the water level is held stationary, and decrease as the water level decreases. The fluid pressure increases during water level increases as the mean normal total stress increases. In the no-fluid-communication condition, the load-induced pore pressure dissipates when the water level is stationary. The effective stress increases with the water level, but at a lesser rate than total stresses. The effective stress increases when water level is stationary until excess pore pressure is dissipated. The effective stress decreases during unloading. The induced shear stress moves with the total stress and the strength changes with effective stress.

160. In cases of fluid communication the results are quite different. The changes in total stress may be less than the change in pore pressure, depending on the location with respect to the reservoir. A time lag is present in the development of pore pressure in low porosity rock due to the necessity of luid flow into areas of fluid pressure increase. The pore pressure may build up to values exceeding the increase in mean total stress for locations outside the reservoir. In these cases the rock mass becomes more unstable with time until an equilibrium pore pressure is achieved. This may take several months. If equilibrium is achieved and a pore pressure reduction occurs, the pressure will remain high until the water can flow out of the area. The effects



ALL LOADINGS ARE PLOTTED AS WATER LEVEL VERSUS TIME

Figure 30. Loading patterns

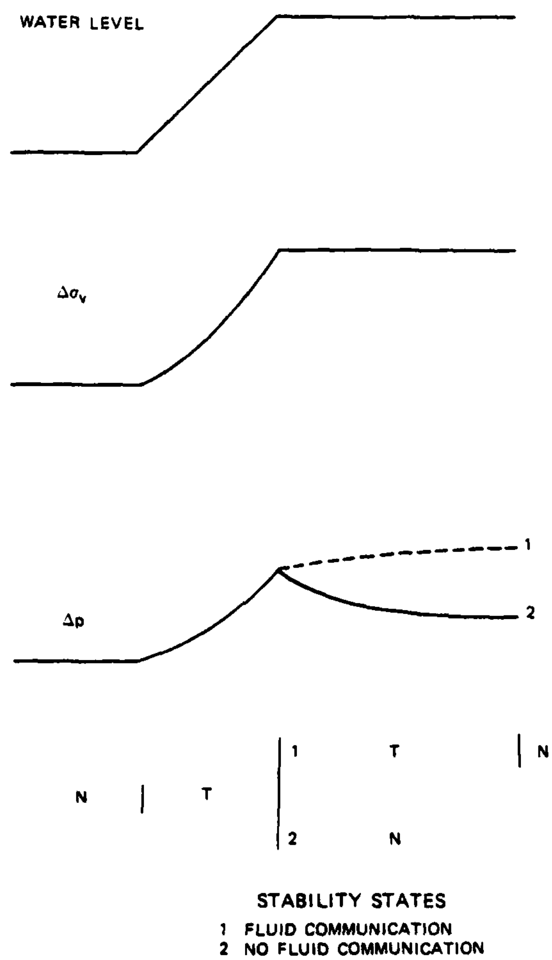


Figure 31. Effects of reservoir loadings A and B

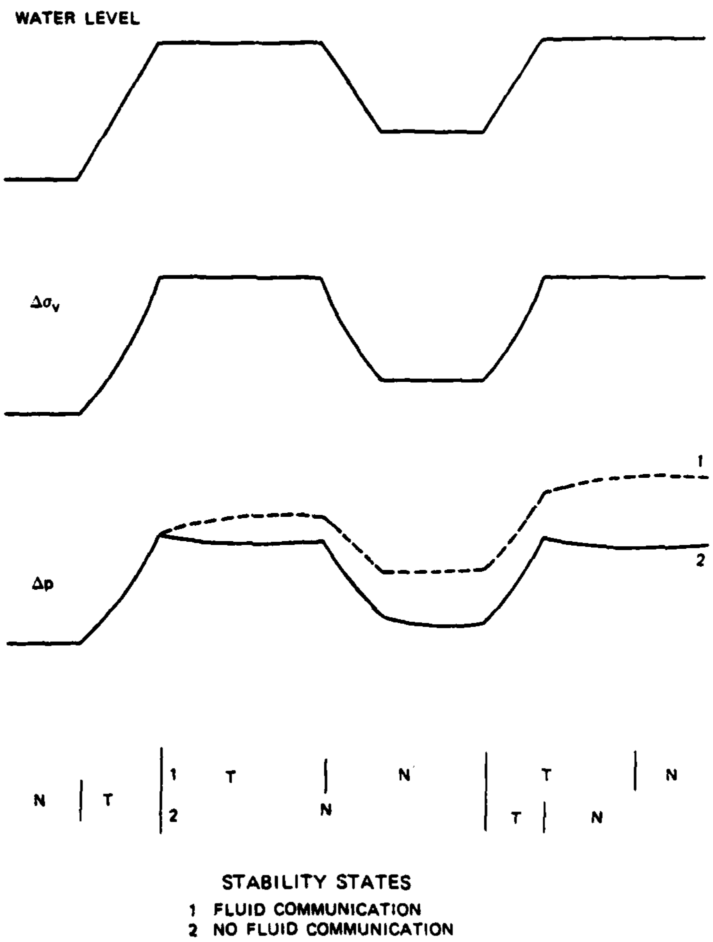


Figure 32. Effects of reservoir loading C

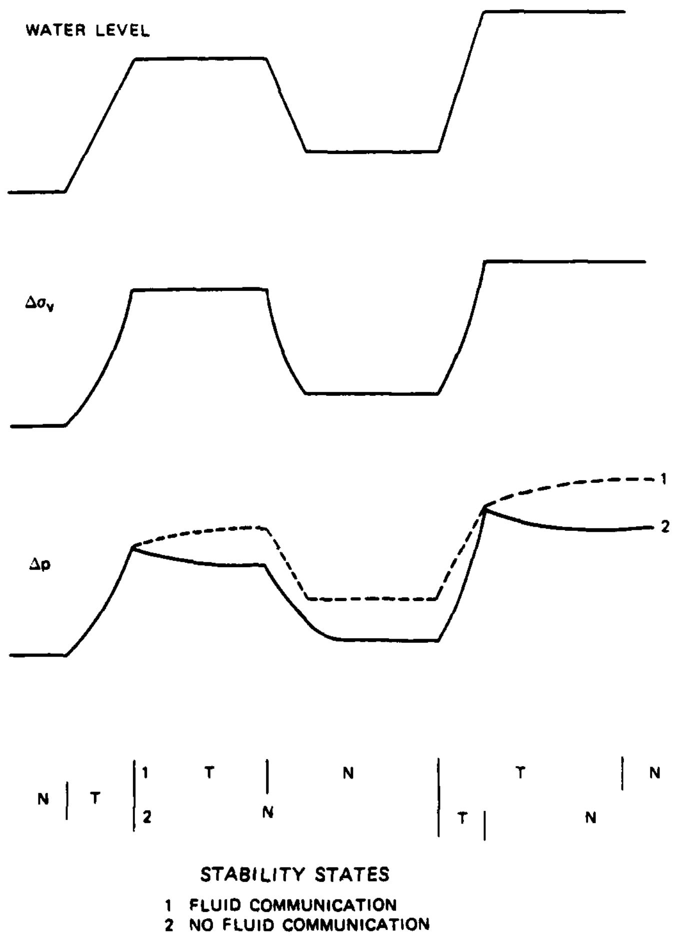


Figure 33. Effects of reservoir loading D

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STATE-OF-THE-ART FOR ASSESSING EARTHQUAKE HAZARDS IN THE UNITED--ETC(U)
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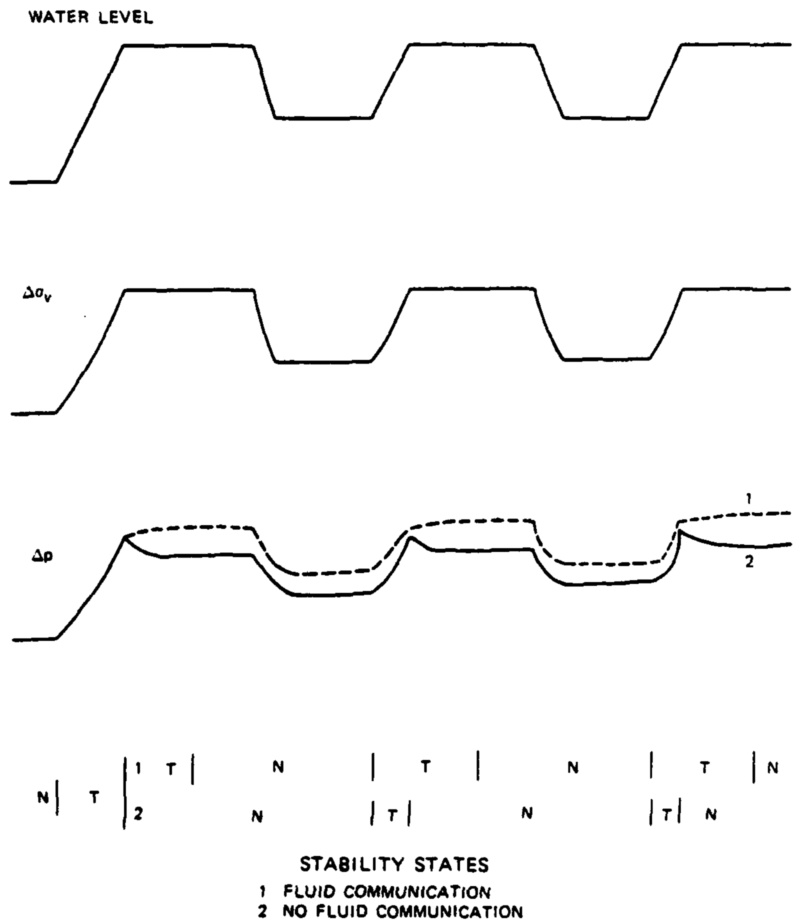


Figure 34. Effects of reservoir loading E

of load-induced pore pressure change and fluid communication pressure change are combined in some field situations. Their combined effect is shown qualitatively in Figures 31 and 34.

Limitations

161. The quality of the interpretation is dependent on the accuracy of the evaluation of the critical variables. The interpretation is sensitive to the assessment of the fluid communication conditions, permeability of the rock mass, and the orientation of principal stresses. The enormous uncertainty associated with the evaluation of these critical variables makes the interpretation very subjective.

b Value Evidence

162. Reservoir-induced seismicity is characterized by a high b value. This statement is based on the observed b values of earthquake sequences thought to be reservoir-induced. Gupta, Rastogi, and Narain (1973) observed that for reservoir-induced seismicity foreshock b values are as high as or higher than aftershock b values and both are higher than regional values or values for normal aftershocks. This opinion has been accepted in the literature and most case studies include b value evidence. The effect of the b value is to give credibility to the idea that a given series of earthquakes was reservoir-induced. This type of evidence is rarely presented alone. It serves to complement other evidence. The purpose of this section is to examine the value of this type of evidence. Several areas that will be examined are the effect of data acquisition and treatment, and the time invariance of b values.

Data acquisition and treatment

163. The b value can be computed for any set of earthquakes. There are conventionally two types of earthquake data used. One type is a set of dependent events like foreshocks, aftershocks, and swarms. The other is composed of independent events drawn from the given region. Once a data set is collected, the preparation of the data is the same in both cases with one exception. Frequently, the main event is not plotted in sets composed of aftershocks. This practice is not universal.

Methods of preparation of a magnitude-frequency relationship can influence the value obtained from the plot. The value can be affected by several factors, such as calculation procedures, magnitude bias, magnitude accuracy, and number of events in the data base. There are several accepted calculation procedures. A straight line can be fit by eye, or the line can be fit using a least-squares method or the maximum likelihood method. The same data subjected to different calculation procedures will render different values. The potential variation depends on the data set. The difference is probably less than ±0.3 for most data sets but may be large (±0.6) in some instances. This judgment is based on examination of many sets of data and comparisons made by Karnik (1971) and Utsu (1969).

164. Magnitude bias is the effect produced by the method of measuring size. Several magnitude scales are in use. The effect of magnitude bias can be seen in Figure 35. A fictitious data set measured in

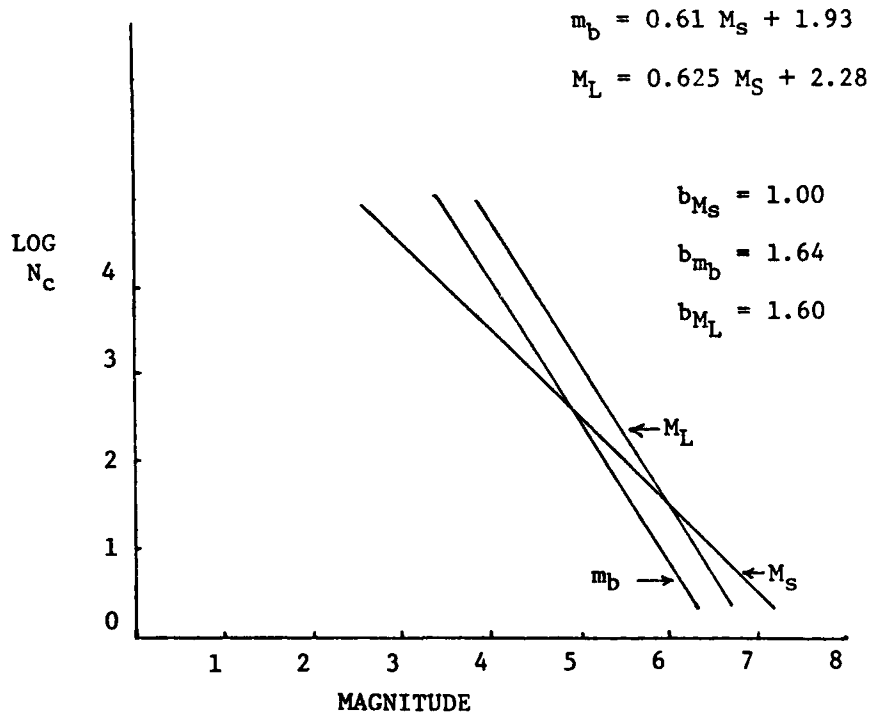


Figure 35. Magnitude bias (magnitude equivalency relationships from Nuttli (1979))

M_s and having a b value of 1.0 was plotted. The data were then converted to m_b , M_L (California), and Richter magnitude M using relationships given by Nuttli (1979). This converted data were plotted on the figure. The b value for M_L and m_b was 1.63 and the value for M was 1.39. The magnitude bias for other types of size measures is not clear. The duration magnitude M_c is drawn from the length of the record on the seismograph. This duration magnitude is frequently used for microearthquakes and may produce a systematically high b value. Talwani et al. (1976) suggest this possibility.

165. The accuracy of the magnitude data pertains to the ability to measure magnitude in fractions of a unit. The level of accuracy determines the number of intervals within a unit of magnitude. This effect is similar to the effect of grouping data. The larger the interval of the group, the fewer the data points and the more uncertainty in the b value. The maximum likelihood method contains a correction for this effect. Utsu (1966) states that the effect of increasing the range for groups systematically reduces the b value when using the maximum likelihood method.

166. The number of events recorded determines the expected statistical variation in the b value. The more events recorded, the closer the calculated value is to the true mean value.

167. In evaluating reservoir-induced seismicity, the magnitude-frequency curves are based on data from groups of related events, foreshocks, and more often aftershocks. Utsu presented a series of papers dealing with aftershocks and earthquake statistics. There is no significant difference in the mean values of aftershocks and independent events worldwide. In specific regions there are differences between foreshock and aftershock sequences. In six of eleven cases reviewed by Utsu (1971) the b value for the foreshocks is smaller than for the aftershocks. This is the opposite of the behavior of reservoir-induced events. Specifically, b values for reservoir-induced seismicity are higher than regional values, and foreshock values are higher than or as high as aftershock values. Is this diagnostic of induced seismicity or is this behavior common to natural seismicity? Table 6 contains b

Table 6

Regional and Aftershock b Values

	b Value	Source*
Kern County, 1934-1963	0.80	1
Kern County aftershocks, 1952	0.90	2
Alaska, 1904-1964	0.65	1
Alaska, 1968	0.68	1
Alaska aftershocks, 1964	1.00	2
Aleutian aftershocks, 1957	1.30	2
Greece, 1966-1967	1.00	1
Thessaly aftershocks, 1954	1.00	2
Zante aftershocks, 1962	1.07	2
Epidavros aftershocks, 1968	1.25	3
Japan, 1926-1956	1.03	1
Nagano Prefecture aftershocks, 1963	1.20	3
Shizuoka aftershocks, 1965	1.40	3

* Source 1 from Evernden (1970); 2 from Papazachos (1974); 3 from Utsu (1971).

values for three areas of the world and b values for aftershocks in that region. These data are not representative, nor were they intended to be. They demonstrate that "normal" aftershock sequences can have b values higher than regional averages. Data regarding foreshocks are more difficult to obtain. In most cases it is difficult to determine whether an event is a foreshock, an independent event, or an aftershock of an earlier event. Foreshocks should be related to the main shock in space and time. An event that occurs at the epicenter of a larger event several hours prior to that event is probably a foreshock. But as the time interval increases or the distance becomes greater, it is not clear how events are related. There is no sure method that will classify an event as a foreshock, independent event, or an aftershock. This makes it vital to examine the raw data when evaluating b values for foreshocks.

168. Given the same data base, it is still possible to arrive at

opposite conclusions. Table 7 shows b values for foreshock and aftershock sequences in Greece. The values determined by Papazachos et al. (1967) are much different from those determined by Utsu (1971). The values of Utsu have foreshock b values higher than aftershock b values. The trends shown by b values are not diagnostic and are greatly influenced by the procedure adopted to calculate the values, magnitude bias, and accuracy of the data.

Table 7

Foreshock and Aftershock b Values

	b Value	
Greece	Source 1*	Source 2
Kephallenia, 1953		
Foreshocks	0.89	0.61
Aftershocks	0.72	0.85
Volos, 1955		
Foreshocks	0.77	0.43
Aftershocks	0.72	0.63

* Source 1 calculation by Utsu (1971); source 2 calculation by Papazachos et al. (1967). Data from Utsu (1971).

Time invariance

169. The use of b values as a seismicity measure, which is claimed to be a characteristic, assumes that the value is time-invariant. Evidence from Koyna presented by Guha et al. (1974) disputes this assumption. It is not clear what method was used to calculate the b values. The data were plotted in the form of magnitude versus the incremental number of events for a given magnitude range. The data usually have a smoother appearance if plotted using the cumulative number of events for all magnitudes equal to or greater than a given magnitude. The yearly b values are given in Table 8. The major event of 10 December 1967 produced a large aftershock sequence. The yearly value for 1967 is for the period up to the large event. The distinction of regional aftershock and foreshock values was not made by Guha et al. (1974). Utsu (1969) claims that no significant variations of b values

Table 8

Koyna b Values

Regional b values, Koyna	
1964	0.84
1965	0.81
1966	0.75
1967	0.72
1971	0.89
1964-10 Dec 1967	0.92
Aftershock b values	
11 Dec-31 Dec 1967	0.84
11 Dec-31 Dec 1971	1.05
Foreshock b value	
1 Dec-10 Dec 1967	0.65

Data adapted from Guha et al. (1974)

have been found in most aftershock sequences. He makes no statement regarding the time stability of regional values or foreshock values.

170. A detailed discussion of b values is given by Karnik (1971). The variation over time of regional b values is shown for Yugoslavia and Greece in Table 9. The b values were eye-fit by Karnik. The change is considerable--0.43 for Yugoslavia and 0.25 for Greece. Guha et al. (1979) uses the change in b values to predict a change in seismicity. A plot of b value versus time is shown in Figure 36. The defense offered by those who believe b to be time-invariant is that the changes are merely statistical fluctuations. The maximum likelihood estimate for Yugoslavia is 1.01. The eye-fit estimate is 0.96. The 95 percent confidence limits of b are $b_L = 0.92$, $b_u = 1.09$ based on the maximum likelihood estimate. Karnik published the data in Table 9 as evidence of the change over time. The values indicated as $\hat{b}$ in Table 10 were determined using the maximum likelihood method. They are very different from the eye-fit values of Karnik. The $\hat{b}$ values were generated so that

Table 9

Time-Varying b Values*

	Yugoslavia			
	1901-1911	1912-1920	1921-1930	1931-1955
Activity b	0.77	0.94	0.93	1.20
$\bar{b}$	0.96			

	Greece		
	1901-1922	1923-1942	1943-1955
Activity b	0.83	1.03	0.78
$\bar{b}$	0.95		

* Data from Karnik (1971).

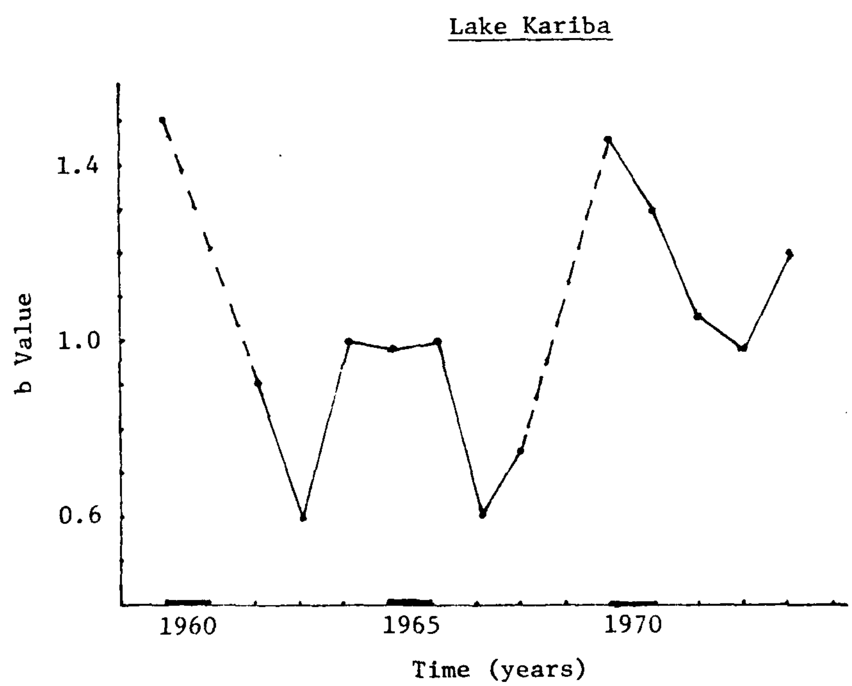


Figure 36. Variation of b value with time (after Guha et al. (1979))

Table 10

Significant Change in b Values Over Time

		95 Percent Confidence Limits, b Values				
		$\hat{b}$	N	b_L	b_u	b
	1901-1955	1.01	238	0.88	1.14	0.96
b_a	1901-1911	0.59	72	0.41	0.73	0.77
b_b	1912-1920	0.84	22	0.49	1.19	0.94
b_c	1921-1930	0.55	93	0.44	0.66	0.93
b_d	1931-1955	0.96	51	0.70	1.22	1.20

$$\frac{\hat{b}_b}{\hat{b}_c} = \frac{0.84}{0.55} = 1.52 \quad F(2n_b,\ 2n_c)_{95} = F(44,186)_{95} \quad 1.50$$

$$\frac{\hat{b}_d}{\hat{b}_c} = \frac{0.96}{0.55} = 1.75 \quad F(2n_d,\ 2n_c) = F(101,186)_{95} \quad 1.43$$

$$F(40,120)_{95} = 1.50$$

$$F(60,120)_{95} = 1.43$$

the statistical variation could be seen. The $\hat{b}$ values were tested against the hypothesis that they were drawn from the same population. The change in $\hat{b}$ value is statistically significant at a 95 percent alpha level. The results are shown in Table 10. This evidence indicates that b values do change with time in some regions and the assumption that the b value is time-invariant should not be accepted without question.

Conclusions

171. The b value is a parameter that may change with time and whose calculation is severely affected by data preparation, magnitude bias, and data accuracy. Given all these limitations, the b value is not diagnostic of induced seismicity. Consequently, b value evidence is meaningless as applied to the discrimination of induced seismicity from natural seismicity.

PART IV: CASE STUDIES

172. Case studies that represent accepted cases of induced macroseismicity were selected for the study. The acceptance of these cases was reported in reports, articles, and books on induced seismicity. The raw data for each of these cases were developed, gathered, and interpreted by individuals who undoubtedly used their best judgment in assessing the data. The incorporation of these cases into the literature results in the final judgment and opinion of the original researchers being reiterated by writers of state-of-the-art or summary papers without reference to the raw data. Once this occurs, the opportunity for alternative explanations of the observed data is lost. The purpose of this report is the review of evidence. In each case the original data, figures, and conclusions are reproduced in enough detail to permit review of the conclusions. In some cases critical data or figures were never published and only conclusions drawn from this data appear in the literature.

173. Each case is reviewed and, when possible, placed into one of nine categories (Figure 1). The nine additional divisions based on b value evidence have been discarded. Presentation of each case will begin with a review of the historical seismicity of the reservoir site that includes the postimpoundment seismicity covered in published accounts. Then, the published correlation evidence is summarized and the original data are reevaluated. Finally, in a summary judgment, other evidence is cited and incorporated into the evaluation. This summary judgment section appears in Part V after the seismicity-based evidence is reviewed. Before individual cases are discussed, certain common features will be mentioned.

Common Features

174. The basic document from which evidence of induced seismicity may be extracted is an appropriately edited catalog of earthquakes. The dependent events must be removed and the locations of the events should

fall within the area of influence of the reservoir. The catalog must be further edited to remove events whose magnitude is lower than the highest detection level for any portion of the record. This procedure must be coordinated with estimation of the area of influence. Estimation of the area of influence has been previously discussed and will be addressed in several of the case studies.

175. Earthquake catalogs are not always available or may be inadequate. Ideally, catalog information consists of a list of earthquakes defined by the five-variable descriptions consisting of size, time, and location. Precise descriptions require the use of seismic detection instruments. Such instruments have only been generally available since the 1950's. Even today the availability of instruments varies widely. In many parts of the world only moderately large events are detected by enough instruments to provide an accurate location and magnitude. Prior to the use of instruments, earthquake size was assessed using intensity (damage) scales. The use of damage scales requires interpretation of earthquake size (energy) based on the effect of the earthquake on surface features, both man-made and natural. The assignment of intensity ratings is influenced by the relative susceptibility of those surface features to damage. The degree of susceptibility is considered in some intensity scales, such as the 1956 modification of the Mercalli scale.

176. The older catalogs that use intensity must be used along with more recent records, which often use both intensity and magnitude to describe size. Correlations between magnitude and intensity are available but must be used with caution. The use of intensity employs the human body as the detection device. To be identified as an earthquake a high percentage of the time, an earthquake usually needs to be rated at IV on the Modified Mercalli scale. By the use of any of the common correlations this is approximately a magnitude 4 earthquake. The use of intensity alone to describe events implies that the M_{md} is about 4 and may be higher. Assume a mild tremor magnitude 4 is felt approximately every 20 years. Assume that this is the true recurrence rate and assume a b value of 0.9 (a typical value). Then during a 200-year period,

these might be 1 magnitude 5 event, 10 magnitude 4 events, 80 magnitude 3 events, and 800 magnitude 2 events. Only about 12 to 14 events would be reported based on human perception. If the region were instrumented and all events of magnitude 3 and greater are recorded, then more than 90 events would be reported for the same period. The increase from 12 reported events to 90 or more represents a magnitude reduction in the M_{md} and indicates no change in the seismicity. The time of occurrence of the event may be recorded very precisely or not at all. The inhabitants of sparsely settled regions may only record the occurrences in their memories. Their recollection as to the number of events and dates of occurrence may be faulty. The location of events may be approximated by the area in the center of the maximum intensity contour. The accuracy of the intensity contours is a function of the number of reports and their individual accuracy. In sparsely settled areas often no credible intensity contours can be drawn. For most of these case histories no accurate catalog exists for the preimpoundment period. This means no data worthy of statistical tests are available for the best known cases of supposed induced seismicity. The fragmentary evidence will be reviewed for each case.

177. Correlation data constitute the largest body of evidence presented to demonstrate induced seismicity. Correlation data are available for each of these case studies. All of the correlation data were interpreted when presented in the original publications. Practices in interpretating the correlations vary widely, but three styles of interpretation can be identified. In this report the styles are called (a) the appearance style, (b) the statistical style, and (c) the theory style.

178. The appearance style evaluates the quality of the correlations by their general appearance. If the peaks in seismicity variable can be matched to peaks in the reservoir variable, the correlation is considered to be good or strong. It is current practice to slide one curve relative to the other to match peaks. The data are usually not discussed; the similarity in the shape of the two parameters plotted versus time is proof enough. The correlation is evaluated as "good," "strong," "clear," or "obvious."

179. The statistical style uses a correlation coefficient to measure the strength of the correlation. The use of a correlation coefficient requires a certain symmetry in the correlated variables. An increase in a variable should produce the opposite effect of a decrease in that variable if the variables are correlated. The statistic that measures correlation is constructed from sets of pairs of variables. During a filling cycle the reservoir variable takes on a certain value twice--once during a rising water level and once during a falling water level. The statistic will indicate a strong correlation if the seismic variable takes on the same value in response to the reservoir variable during both rising and falling water. If the reservoir effects on the crust are different during rising water than they are during falling water, the statistic should not indicate a strong relationship.

180. The third style of interpretation uses a mechanistic theory of triggering to evaluate the correlation. This style offers the flexibility to incorporate site-specific information to interpret the relationship between the reservoir and the observed seismicity.

Hoover Dam/Lake Mead

Earthquake history

181. Located on the Colorado River southeast of Las Vegas, Nev., this reservoir was the largest in the world until surpassed by Lake Kariba about 1958. The reservoir is a multivalley lake which extends upstream about 115 km from Hoover Dam located in Black Canyon to the lower reaches of Grand Canyon. A location map is shown as Figure 37. Before construction the area was sparsely populated by white settlers. Indians had once occupied this region but by the early 1900's they were relocated to reservations. The area is a desert whose few inhabitants were miners. The largest settlement was Las Vegas, located about 30 miles (48 km) to the northwest of the dam. Las Vegas, during the era from 1905 to about 1931, was a railroad town whose population in 1920 was about 2300 and had grown to about 5000 in 1931. Present-day Boulder City did not exist prior to 1931. The only settlements in the immediate

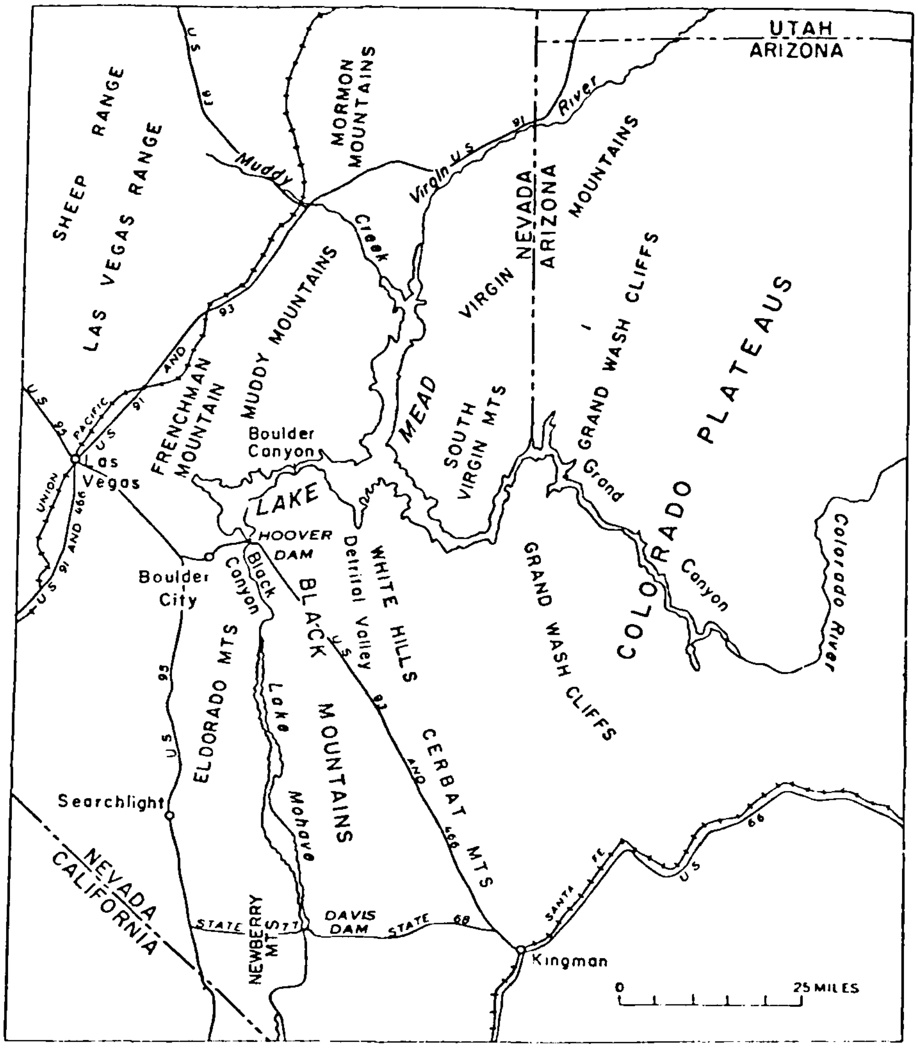


Figure 37. Hoover Dam/Lake Mead location map
(after Longwell (1963))

area of the present reservoir were the little Mormon community of St. Thomas and the tiny old abandoned settlement at Callville.

182. The postimpoundment seismicity is concentrated near the dam in Black Canyon. Callville, the closest settlement, was about 7 km north of the damsite. No mine works appear to be closer to the damsite. The closest instrumental detector was located in Reno at the University of Nevada and had been operating intermittently since 1906. Based on a

list of Nevada earthquakes prepared by Slemmons et al. (1965), only one earthquake was recorded in Nevada south of Las Vegas from 1852 to 1936. This one reported earthquake was intensity V and was not near the reservoir area. It appears that an event would need to be about magnitude 4.5 to be detectable at Reno.

183. The level of perceptibility of events in the Lake Mead region is discussed by Jones (1944). He judges that events of magnitude 4.0 had a 50-50 chance of being felt at a distance of 21 miles. Las Vegas is about 30 miles from the damsite. It appears that only events of magnitude greater than 4.0 would likely be felt at Las Vegas. Many more of these shocks would be felt in Callville. Jones (1944) states that "no earthquakes were reported by the few local inhabitants in the 15-year period prior to the construction of Boulder Dam." A similar report appeared in Engineer News Record in May 1937. The question of where these local inhabitants lived is important. People living in Las Vegas or St. Thomas would feel very few, if any, earthquakes below magnitude 4.0 and may not recognize the sensation as an earthquake. Locals from Callville would stand a far greater chance of recognizing small earthquakes in the proposed damsite vicinity. Nevertheless, it appears that no events of magnitude 4.5 or larger took place near the dam from 1921 through 1935.

184. Rogers and Lee (1976) present a list of events where $M_L \geq 4.0$ or MM Intensity $\geq$ V. This list appears as Table 11. This list was further edited to exclude events $M_L < 4.5$ and to require epicenters to be lat. 36.0 ± 0.2 N, long. 114.7 ± 0.2 W. This region is shown in Figure 38. The edited list of events appears in Table 12. In the source zone as shown in Figure 38, seven earthquakes of $M_L \geq 4.5$ occurred in the 15 years after impoundment; whereas, no events of $M_L \geq 4.5$ occurred in the 15 years prior to impoundment. The source zone is obviously within any reasonably estimated area of influence of the reservoir. It is assumed that the detection of $M_L \geq 4.5$ or larger events is complete for this source zone from 1921 through 1964. It is tempting to perform some statistical tests on this data, but the data are simply too crude to justify any such testing. There has been an increase

Table 11

All Historical Lake Mead Events with
$M_L \geq 4.0$ or Modified Mercalli Intensity $\geq$ V

Date	Time GCT	Lat. N	Long. W	M_L or m_b	Intensity	References and Remarks
09/07/36	11:48	36.0	114.8	4.5	IV	S
09/20/36	04:13	36.0	114.8	3.5	V	UF
04/28/37	04:15	36.0	114.8	4.0*	V	UF
04/28/37	06:16	36.0	114.8	4.0**	V**	U
06/18/37	17:18	36.0	114.8	4.0*	V	UF
11/12/37	00:39	36.0	114.8	3.5	V-VI	UF, felt in Las Vegas
07/28/38	00:01	37.6	115.8	4.0	IV	S, GS, felt at Boulder City and Hoover Dam, mislocation?
07/28/38	00:39	37.6	115.8	4.5	V	S, GS, felt at Boulder City and Hoover Dam, mislocation?
12/28/38	04:38	36.8	114.1	4.0	IV	S, GS
05/04/39	20:44	36.0	114.8	5.0	VI	UF, RJ, felt in Las Vegas
05/04/39	22:37	36.0	114.8	4.0	IV	S, GS
06/11/39	19:15	36.0	114.8	5.0**	VI**	S, felt by all, rock slides, plaster cracked and fell
06/04/42	15:26	36.0	114.9	4.0*	V	UF
08/11/42	10:14	36.0	114.7	4.0	V	S, GS
09/09/42	05:15	36.0	114.7	5.0*	VI	UF, GS, felt in Las Vegas
06/11/44	05:19	39.0	116.0	4.0	IV	S, GS, felt at Boulder City, mislocation?
07/30/47	22:45	36.0	114.8	4.5**	V-VI**	S, U, RJ, felt by all, dishes rattled, bushes shaken
09/30/47	21:58	36.0	114.8	4.0*	V	S, GS
05/09/48	18:53	36.0	114.8	4.0*	V	S
11/02/48	16:48	35.9	114.8	5.0*	VI	UF
05/07/50	08:36	36.0	114.8	4.0*	V	S
02/08/52	08:59	36.0	114.8	3.4	V	UF
02/20/52	13:41	36.0	114.8	5.0*	VI	UF, felt in Las Vegas†
05/24/52	04:15	36.1	114.8	5.0	VI	UF, S, GS, felt in Las Vegas†
10/18/52	19:55	36.0	114.8	4.0*	V	U, S
10/20/52	07:26	36.0	114.8	5.0*	VI	S, GS
04/19/58	09:01	36.0	114.9	5.0*	VI	UF
03/25/63	09:29	36.0	114.9	4.3m_b	VI	UF, U, felt in Las Vegas
04/23/63	08:13	36.0	115.0	4.0*	V	UF
09/23/64	17:10	35.9	114.8	4.4m_b	V	UF, U, felt in Las Vegas

Note: Sources of information are U. S. Earthquakes (U), Coffman and von Hake (1973) (UF), Slemmons et al. (1965) (S), the Las Vegas Review Journal (RJ), Hays et al. (1975)(GS). Data from Rogers and Lee (1976).

* Magnitude estimated from intensity.

** Intensity and magnitude estimates by authors from felt data.

† Magnitude 5.0 events not reported in the RJ.

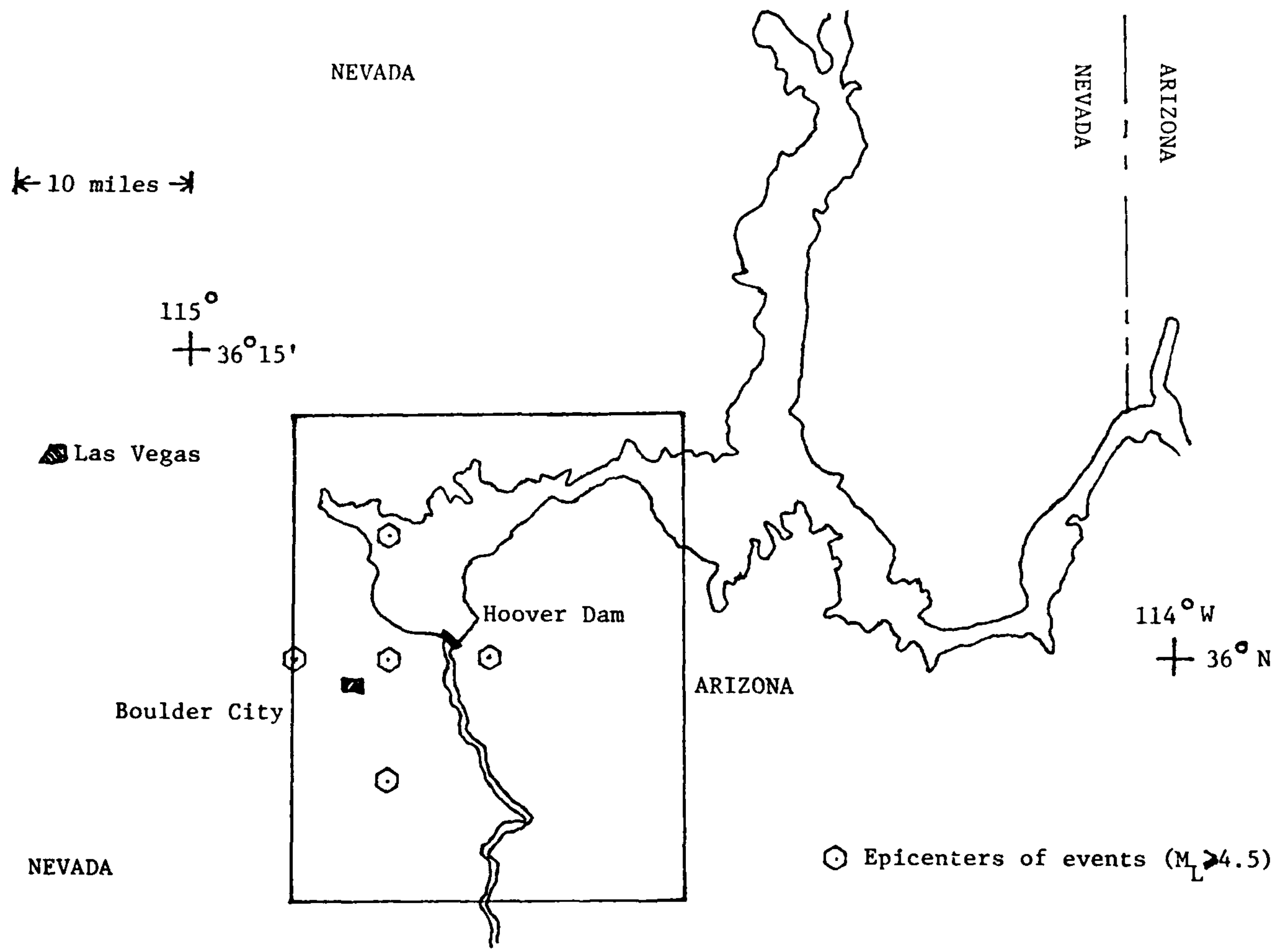


Figure 38. Location of macroseismicity at Lake Mead, 1936-1948

Table 12

All Historical Lake Mead Events
with $M_L \geq 4.5$ or Modified Mercalli Intensity $\geq$ V

Date	Lat. N	Long. W	M_L or m_b	Intensity
09/07/36	36.0	114.8	4.5	IV
05/04/39	36.0	114.8	5.0	VI
06/11/39	36.0	114.8	5.0*	VI*
09/09/42	36.0	114.7	5.0**	VI
07/30/47	36.0	114.8	4.5*	V-VI*
11/02/48	35.9	114.8	5.0**	VI
02/20/52	36.0	114.8	5.0**	VI
05/24/52	36.1	114.8	5.0	VI
10/20/52	36.0	114.8	5.0**	VI
04/19/58	36.0	114.9	5.0**	VI
03/25/63	36.0	114.9	4.3m_b	VI
09/23/64	35.9	114.8	4.4m_b	V

Note: After Rogers and Lee (1976).
* Intensity and magnitude estimates by authors from felt data.
** Magnitude estimated from intensity.

in seismicity for events of magnitude $M_L \geq 4.5$ or greater in this source zone which is coincident with impoundment. Assign this case to category I.

Correlation data--
original findings

185. Correlation data has been presented by several authors, first by Carder (1945), then Carder (1970), and most recently by Rogers and Lee (1976). Mickey (1973) reviewed cases of induced seismicity and presented a correlation drawn from Carder's data. Carder used two reservoir variables, water level and water load. He also used two seismic variables, number of events per week and log energy release per week. The number of earthquakes was presented several ways, as felt events, reported events, and later the data were consolidated as events per month. The data are shown in Figures 39, 40, and 41. The plot in Figure 39 is from Carder (1945). The data were referred to as the "factual relation between seismicity as defined above and the water level of Lake Mead over the years 1935 to 1944." The definition was the count of earthquakes occurring in the immediate vicinity of Lake Mead and at focal distances not in excess of 70 miles from Boulder City. Carder discussed the graph, noting that the peaks in seismicity did not always occur during peaks in load. He noted that the highest seismicity in terms of number of events and energy took place in May 1939 during a seasonal rise at a time when the lake level was lower than the 1938 maximum level. The emphasis in the article was on the effect of load. It is important to realize that both seismology and rock mechanics were far less developed fields at the time of this article. The concept of effective stress was known, but was not generally considered in geology or rock mechanics at this time. It was 14 more years before Hubbert and Rubey (1959) would popularize the role of effective stress in crustal deformation. In Carder's pioneer article the correlation was constructed using the knowledge that earthquakes were caused by movement along faults. Carder contended that geologic evidence suggests pre-Pliocene subsidence occurred in Callville Basin and that the subsidence was "being renewed under the stimulus of tens of billions of tons of lake

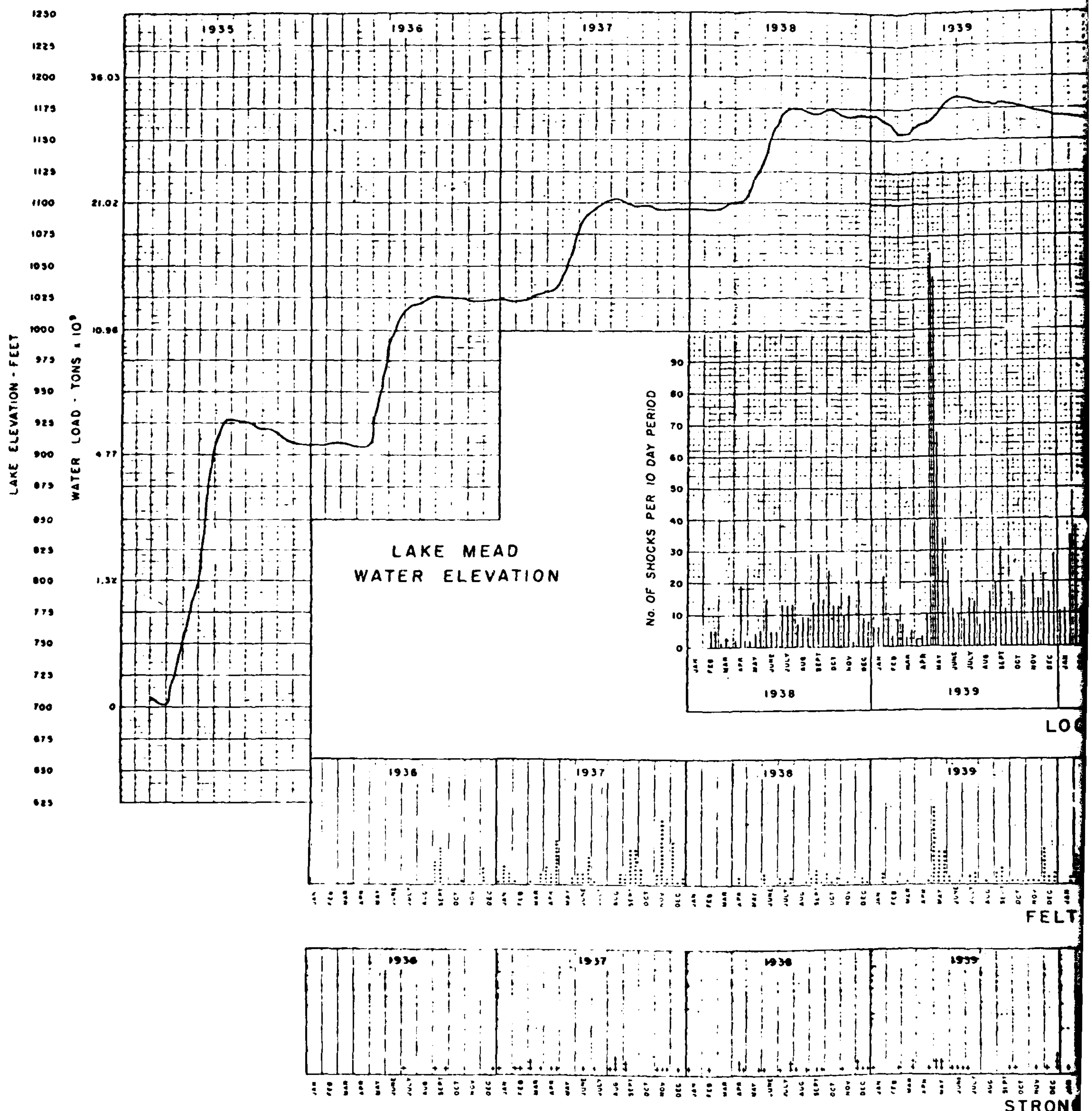
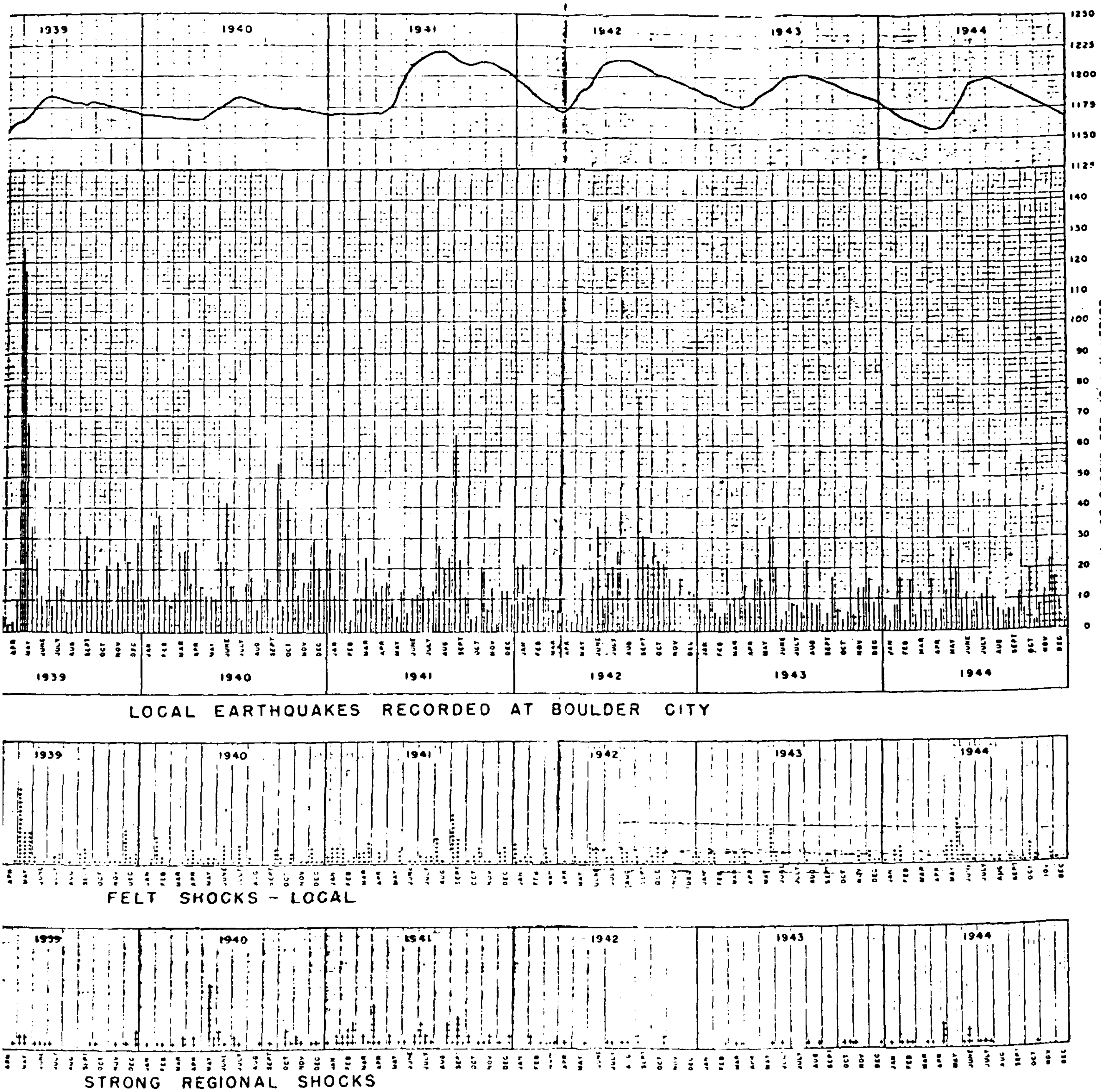


Figure 39. Correlation data, Lake Me



data, Lake Mead, 1936-1944 (from Carder (1945))

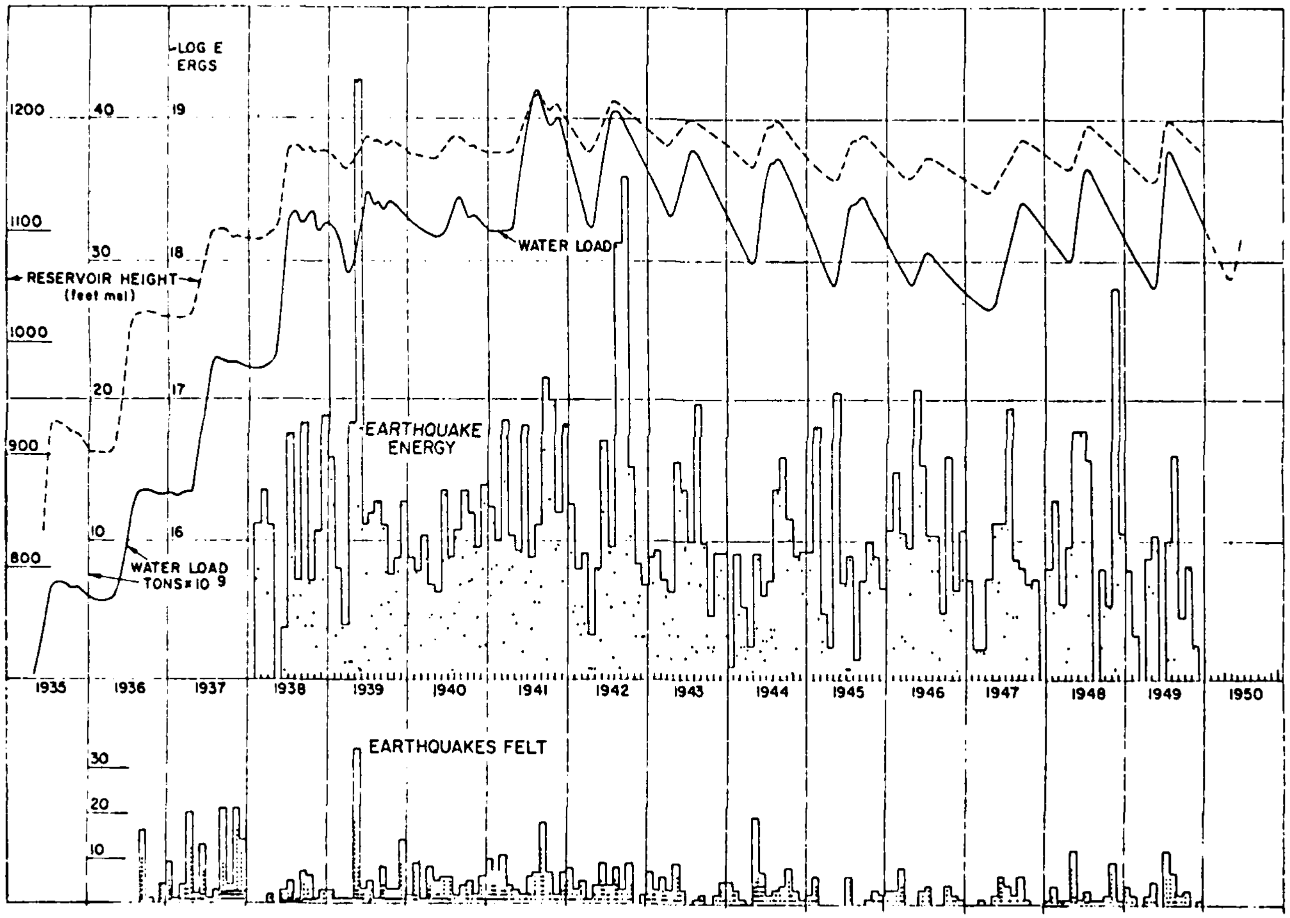


Figure 40. Correlation data, Lake Mead, 1936-1949 (from Carder (1970) with permission of American Geophysical Union)

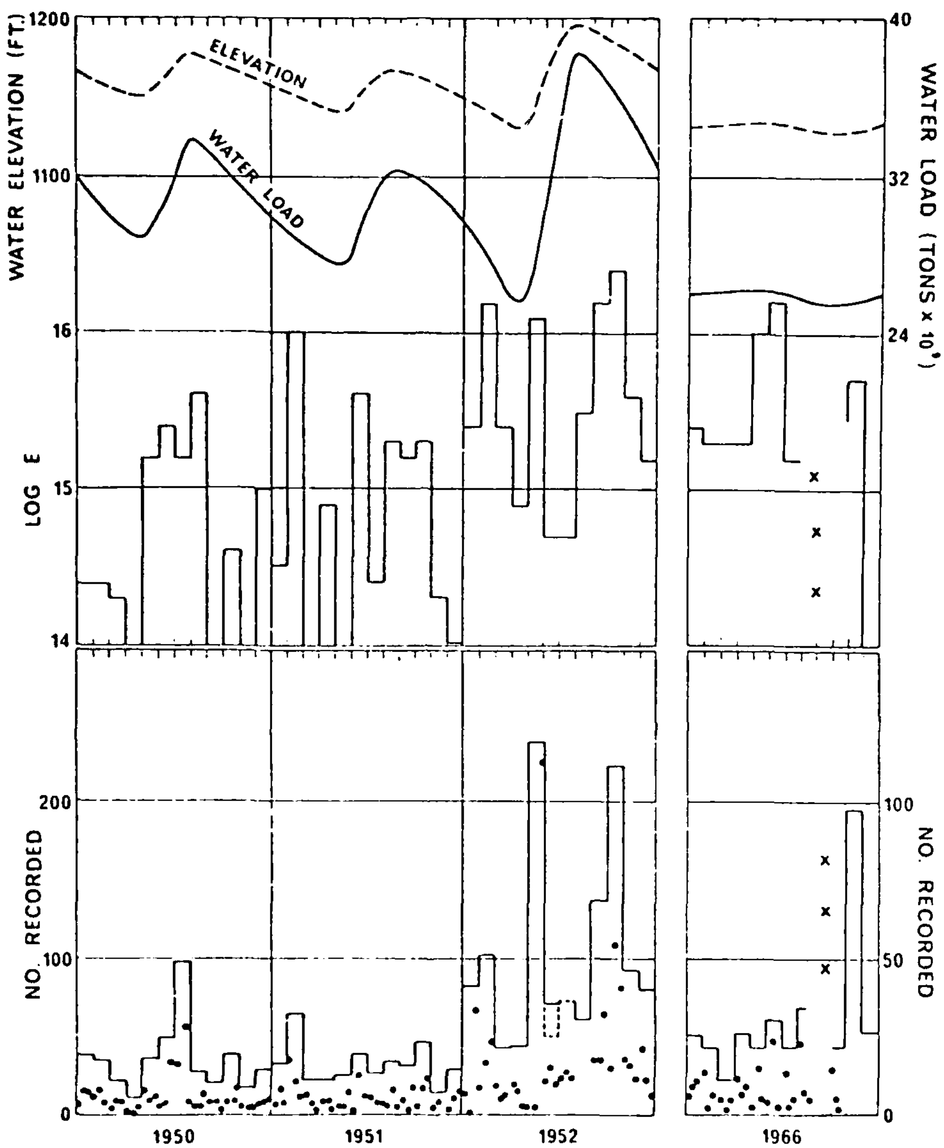


Figure 41. Correlation data, Lake Mead, 1950-1952, 1966 (from Carder (1970) with permission of American Geophysical Union)

water." Carder reasoned that the small energy released in the shocks at Lake Mead were commensurate with the predicted elastic displacements. Carder considered the crust to be large fault-bounded blocks. The lake loading on these blocks caused movement of the boundary faults. He concluded that "shocks seemed to be more closely associated with seasonal increase or peak loads." The early article used a mechanical notion of crustal behavior to identify water load as the important reservoir variable. The number of shocks per 10-day period was adopted as the seismic variable although energy release was discussed. Carder attempted to relate local geology and the seismicity by identifying block boundary faults. The seismic instrumentation provided epicentral locations for some events. The average error in location was considered to be about 1 mile. Although his notion of how the earthquakes were caused led him to select water load as a variable, he did not interpret the correlation in terms of a mechanical model. His representation of correlation data followed the appearance style. The seismic variable was loosely defined as the number of events within 70 miles of Boulder City. The peaks in load were compared to peaks in seismicity and qualitatively pronounced "closely associated."

186. Carder (1970) reviewed all the correlation data collected in 1970 and presented correlation data in two figures. One figure displayed data from 1935 to 1949. These are shown in Figure 40.

187. Carder concluded that there was "strong evidence" that the events of May 1939 had some correlation with the peak load of the previous year and were "triggered by the rapidly rising water in 1939." He adds that "for the same reason" the energy and frequency peak during the summer of 1942 may be related to the all-time load maximum of 1941 and might have been triggered by the load of 1942. The use of the expressions "strong evidence" and "for the same reason" must refer to the appearance of the plots since no statistical measures were used and no theory was used to explain the association between the reservoir variable and the seismic variable.

188. During 1972 and 1973, Rogers and Lee (1976) monitored microseismic activity at Lake Mead. They present correlation data shown in Figures 42 and 43. Using reservoir level as the reservoir variable and two seismic variables, number of events per 10-day period and log energy release per 10-day period, they calculated a correlation coefficient of 0.48 between the lake level and the seismicity and indicated that the hypothesis that the correlation coefficient r is zero can be rejected at

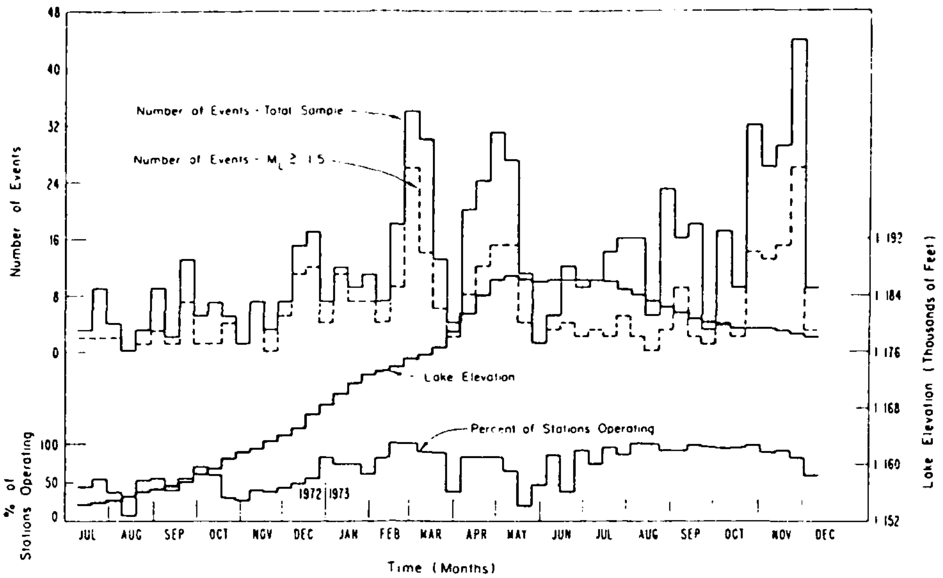


Figure 42. Correlation data, Lake Mead, 1972-1973, number of events (after Rogers and Lee (1976))

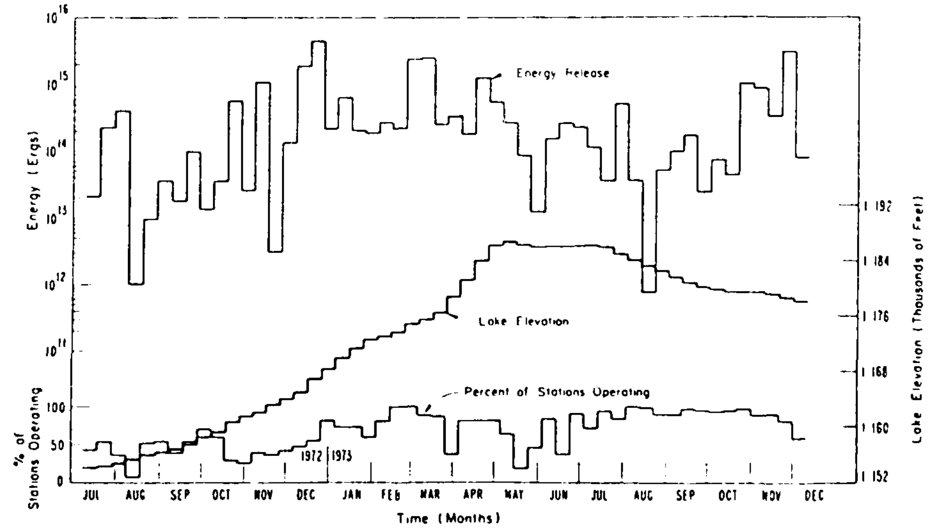


Figure 43. Correlation data, Lake Mead, 1972-1973, energy (after Rogers and Lee (1976))

a one percent significance level. They acknowledge that the number of events is influenced by a station effect. The more stations that are operating, the more events are recorded. If only events with $M_L \geq 1.5$ are considered, there is a decrease in seismicity with a rising lake level. When the log energy is correlated with the lake level, $r = 0.25$. The hypothesis that the correlation coefficient is zero cannot be rejected at a 5 percent level of significance Rogers and Lee have opted to use the second style of interpretation that relies on the use of statistical measures. They conclude that for their data there is no correlation between lake level and seismicity.

189. In 1973, Mickey published a correlation between water level and number of events in a form designed to show the periodicity and correlation between water level and number of events per 3-month period. The correlation was said by Mickey to be "very apparent" but to have "a low level of significance." Mickey grouped the data into four 3-month periods for the years 1939 to 1951. He stated that when other averages or monthly combinations were used, the correlation was much less apparent. Mickey did not use any statistical measure and relies on the appearance of the plot to represent its quality.

Correlation data--discussion

190. Many hundreds of events have been located in the Lake Mead area. Almost all of the larger events ($M > 4$) have occurred south of Boulder Basin from Boulder City to Fortification Hill. It is this location that is shown in the box in Figure 38. The focal depths of those events are not known. The area contains many faults and no particular fault is associated with the larger events. Examination of the water level and load show that the total stress and pore pressure were increasing from 1936 to 1941. There is evidence of deep fluid communication since several warm springs were encountered in the Nevada abutment during construction. This means that a fluid communication time lag may be present. It will be assumed that the time lag does not exceed 1 year even at a depth of several kilometres. This assumption is untestable but is conservative based on the calculation of Howells (1974). So the stability state is T from 1935 to 1942. After 1942 to

1947 there was a general decrease in peak annual load. The pore pressures during this time may have remained high but should have been decreasing with time. From 1943 to 1947 all declines in load are assigned stability condition N . During load increases the stability state is T . The only large event that occurred during this period (1943-1947) took place during a rapid increase in load in 1944. Beginning with 1947 the annual peak load increased through 1949. All of these events occurred during periods of increased load. During November 1948 an event took place during a declining water level. The region has seen greater stress and larger pore pressures. This event probably was not triggered. The event of May 1950 took place during a rising water level. The event of February 1952 took place during a falling water level and reducing pore pressures and was not triggered. During May 1952 the water level was rising rapidly when an event took place. The events of October 1952 took place during declining load, but pore pressure may have been rising and a determination of the stability state is not possible. The events of March and April 1963 took place under declining load, but the pore pressure may have been rising due to the mid-1962 rise in load. The event of 1964 occurred under declining load and pore pressure and was not triggered.

191. Table 12 summarizes the larger events occurring within the block in Figure 38. Of the 12 events, three were not triggered, eight may have been triggered, and one cannot be evaluated. After 1964 the lake inflow was regulated by Glen Canyon Dam upstream of Hoover. The seasonal changes are much milder. No events (M J 5) have occurred in the blocked area since 1964. There is a positive correlation between the seismicity and reservoir. Assign this case to correlation category +.

Kariba

Earthquake history

192. In 1958 the impoundment of Lake Kariba created the largest sustained loading that man has imposed on the surface of the earth. Since the impoundment several large earthquakes have occurred. Prior to

the impoundment of the lake, no seismological observatories existed in its vicinity. Snow (1973) cites a geologist, Bond, who gives evidence that the Binga fault which traverses the western portion of the lake was active prior to impoundment. It was reported by Snow (1973) and Gupta and Rastogi (1976) that no preimpoundment earthquakes originated in the northeast end of the lake. However, no evidence whatsoever is presented to verify this. In fact, Gough and Gough (1970b) report, "No control observations from near seismographs are available for the level of activity before closure of the dam. At least one fault, that at Binga, near the west end of the lake, was active before the lake was filled and . . . others may have been active at a low level."

193. Stations in Africa capable of monitoring large events occurring before construction of Kariba were located in Cape Town, Johannesburg, Tananarive, and Helwan as shown in Figure 44. In a continuing

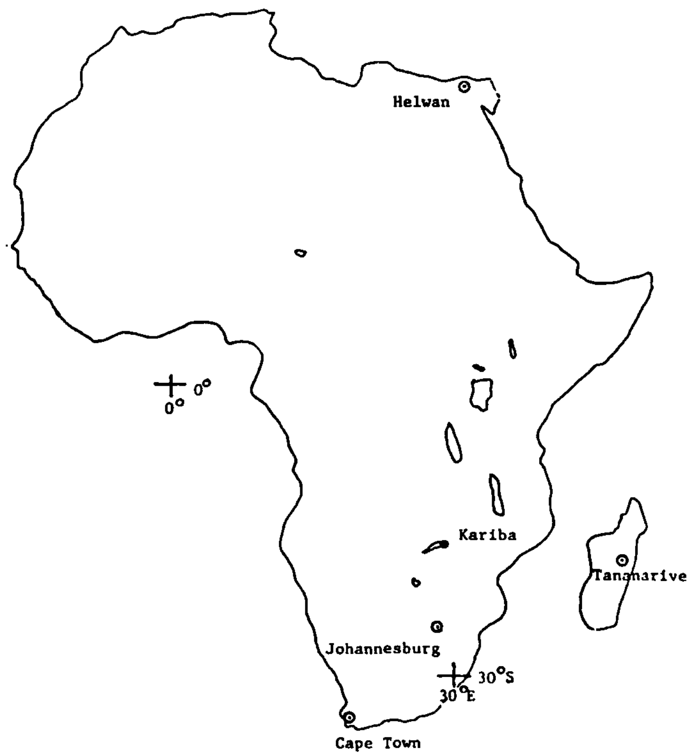


Figure 44. Seismic stations near Kariba before 1958

study by UNESCO (Rothe 1969), the number of events recorded in continental Africa since 1953 is 74 as compared to one event reported before 1953. The study provides statistical treatment for events whose magnitude is equal to or larger than 6.0. It is assumed that this is the minimum magnitude of complete detection for the UNESCO study.

194. The UNESCO study reports five events occurring within a 50-hr period in September 1963 in an area defined by a rectangle, lat. 16.6 ± 0.4 S, long. 28.5 ± 0.5 E, in Figure 45. The maximum magnitude

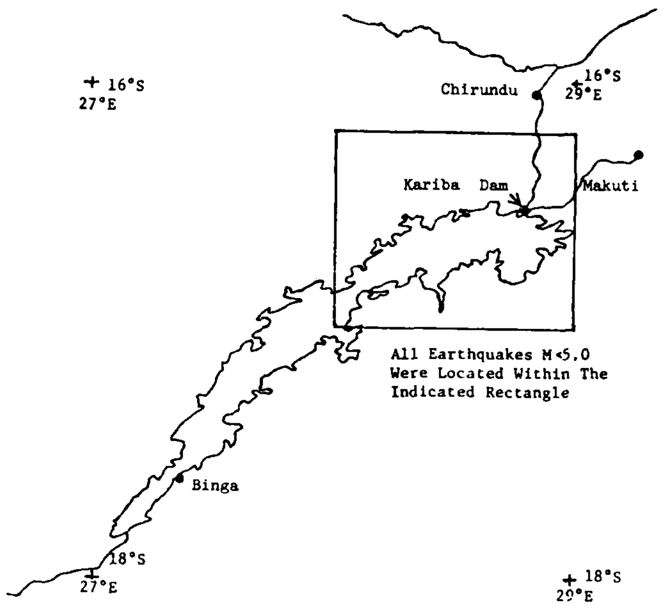


Figure 45. Kariba region

is reported by Gough and Gough (1970b) as 5.8, and this value will be used in this report. The events reported by Gough and Gough are given in Table 13. A modified list which includes only independent events whose magnitude is >4.5 is given in Table 14. The definition of independence used in this table is that independent events cannot occur within 3 days of a larger event. It is assumed that the events of 23-25 September are represented as one event, magnitude 5.8.

195. Sufficient information to judge the felt areas of the events is not presented. The population near the reservoir before impoundment

Table 13

Events at Kariba*

Date		Magnitude m_b	U.S.C.G.S.		J.E.D.	
			Latitude	Longitude	Latitude	Longitude
1961	July 3	--	16.28S	28.77E	--	--
1961	Sept. 13	4.0**	17.01S	27.76E	--	--
1963	Aug. 14	3.7**	16.7S	28.7E	16.60S	28.87E
1963	Sept. 23	5.5	16.6S	28.6E	16.60S	28.47E
1963	Sept. 23	4.7**	16.7S	28.7E	16.59S	28.70E
1963	Sept. 23	5.8	16.6S	28.8E	16.58S	28.46E
1963	Sept. 23	4.9**	16.7S	28.4E	16.67S	28.40E
1963	Sept. 23	5.5	16.6S	28.7E	16.66S	28.54E
1963	Sept. 24	5.0**	16.6S	28.7E	16.64S	28.54E
1963	Sept. 25	5.8	16.7S	28.7E	16.70S	28.58E
1963	Oct. 5	4.9	16.9S	28.6E	16.75S	28.62E
1963	Nov. 8	5.5	16.5S	28.5E	16.63S	28.56E
1966	Apr. 5	4.2**	16.40S	28.52E	16.37S	28.64E
1967	Apr. 20	5.5	16.69S	28.19E	16.64S	28.26E
1968	June 5	3.4**	16.8S	28.3E		

* After Gough and Gough (1970b).

** Denotes magnitude estimate by Archer and Allen (1969). Other magnitudes are from U.S.C.G.S. bulletins.
J.E.D. = joint epicentral determination.

Table 14

Larger Events at Kariba

Date		m_b	Location			
			U.S.C.G.S.		J.E.D.	
			Latitude	Longitude	Latitude	Longitude
1963	Sept. 25	5.8	16.7S	28.7E	16.70S	28.58E
1963	Oct. 5	4.9	16.9S	28.6E	16.75S	28.62E
1963	Nov. 8	5.5	16.5S	28.5E	16.63S	28.56E
1967	Apr. 20	5.5	16.69S	28.19E	16.64S	28.26E

consisted of native Africans. Resettlement of people from the reservoir area provides population figures for the reservoir area. The total is estimated at 50,000 (Scudder 1973). Despite the presence of the Africans at the site, no information is published regarding the absence or presence of preimpoundment seismicity. The record of postimpoundment seismicity includes four events in about 7 years of monitoring. Because of this dearth of information no judgment can be made concerning a post-impoundment change in seismicity. Assign the case to category Q.

Correlation evidence--
original findings

196. Gough and Gough (1970b, 1976) present correlation data for Kariba. They chose as reservoir variables, water level and stressed volume. Stressed volume is the zone within which the reservoir load produces a shear stress in excess of one bar. The seismic variables selected were number of events per week and log energy release per week. The data appear in Figures 46 and 47. The Goughs used a descriptive style to evaluate the data. Peaks in stressed volume were associated visually with peaks in seismic variables. The authors concluded that the stressed volume was "highly correlated" with seismic activity as the lake filled for several years thereafter until mid-1966. No statistical measures were used and the correlation data as a whole were interpreted without reference to a model.

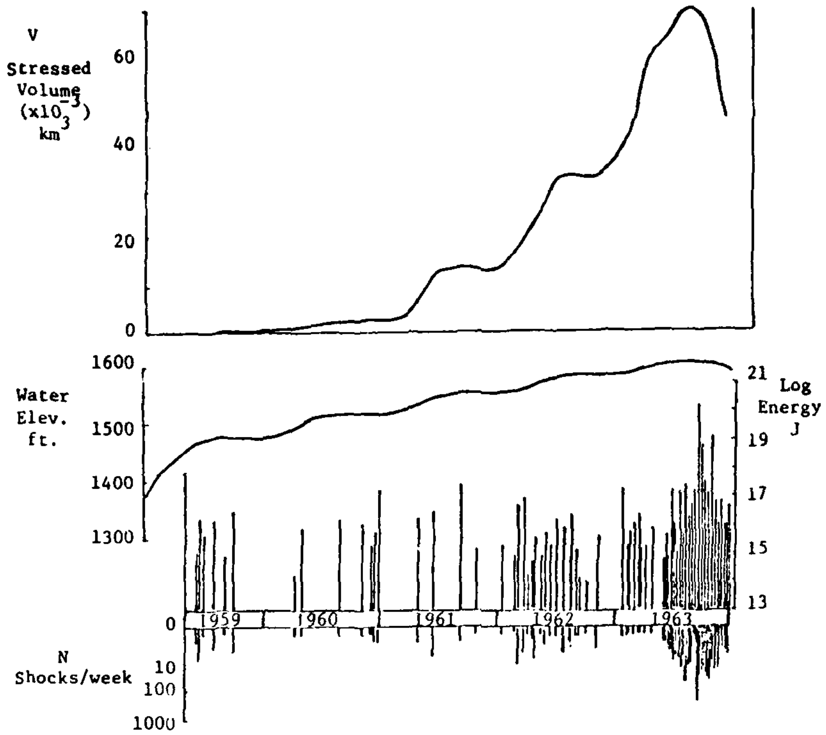


Figure 46. Correlation data, Kariba, 1959-1963
(after Gough and Gough (1970b))

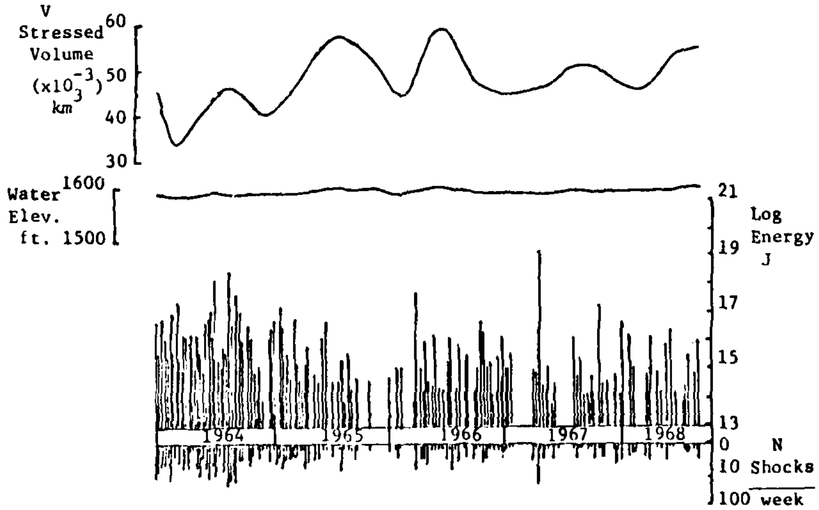


Figure 47. Correlation data, Kariba, 1964-1968
(after Gough and Gough (1970b))

197. Portions of the correlation data were used to select the most likely of three failure mechanisms for selected sets of earthquakes. The postulated earthquake generating processes (failure mechanisms) are paraphrased:

a. The weight of the water directly causes crustal failure.

b. The weight of the water adds stress to a larger initial stress and triggers failure.

c. The effect of increased groundwater pressure causes failure.

198. The seismic activity was divided into three groups. Group 1 was called the main activity and included all ($M \geq 4$) shocks. This activity took place in the eastern end of the lake (Figure 45). Group 2 took place north of the lake in the valley downstream of the dam near Chirundu, and Group 3 took place near Binga in the western end of the lake. The Goughs used their calculations of induced stress and some intuitive arguments to assess how the reservoir induced these earthquakes. This was not using correlation evidence to establish whether a relationship existed between the reservoir and the seismicity. In their discussion it is assumed that a relationship did exist and the data were used to devise the mechanism of triggering. The possibility that the seismicity was unrelated to the reservoir was not considered.

Correlation data--discussion

199. The earthquakes at Kariba were monitored using a local seismic array. Because of the large distances involved, the three station arrays located only 159 of over 2000 events recorded during the years 1961 to 1963. The larger events of a few sequences are listed in Table 14. There is no evidence of fluid communication. It was believed that the reservoir was underlain by a relatively impervious mudstone, but the geologic details are vaguely reported in the literature. Since the site has had such few periods of significant seismicity, it is not possible to draw any conclusions. Certainly the 1961 and 1963 sequence might have been triggered. The April 1967 event was probably not triggered. Assign this case to Category Q.

Kremasta

Earthquake history

200. During 1964 a high dam was completed on the Acheloos River in central Greece. The reservoir level rose to el 259.2 m, some 20 m below maximum operating water level, on 5 February 1966, when an earthquake of magnitude (M_s) 6.3 took place. Greece is a moderately active seismic region, but no events near the location of the reservoir had occurred before impoundment. The records go back to 1872.

201. In the case of a region of moderate to high normal seismicity, it is essential to accurately estimate the area of influence of the reservoir. In the two previous cases the major postimpoundment seismicity occurred very close to the damsite. Consequently, the dimensions of the area of influence were not critical. In a more active seismic environment the determination of the area of influence is important. Detailed studies should be carried out to determine groundwater divides. To make a confident estimate, much more detailed information is required but a conservative approximation will be obtained using the available data.

202. Initially, the area can be described by the surface drainage divides appearing on a topographic map. The initial dimensions of the area of influence are 20 km from the reservoir boundaries, or midway between the reservoir and streams outside the reservoir drainage basin. This first approximation is shown in Figure 48, indicated by a solid line. The reservoir sits astride the Pindus thrust fault and is cut by several normal faults in the immediate vicinity of the dam (Snow 1972) and a wrench fault called the Alevrada-Smardacha fault which cuts the northern finger of the reservoir. Lake Trichonis, a large natural lake, also straddles the Pindus thrust fault.

203. A geologic cross section for the region is given by Jenkins (1972). A plan and cross section are given in Figure 49. The reservoir bottom is predominantly flysch. North of the Alevrada fault the reservoir bottom is in Cretaceous limestone. This limestone is solutioned and the river shows the consequences of this near Sivista. Snow claims

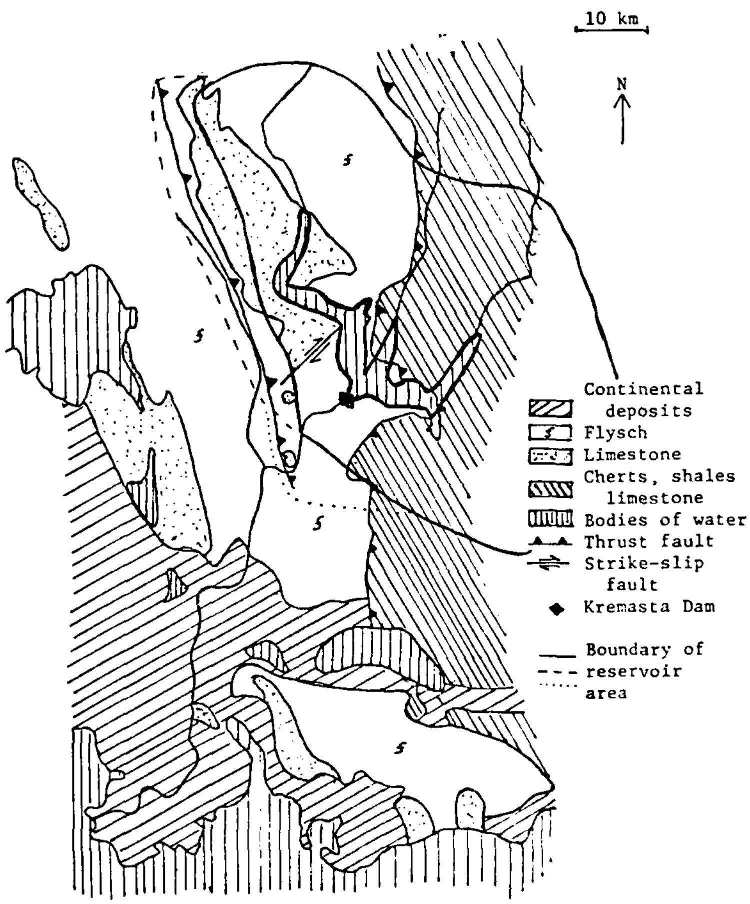


Figure 48. Surface geology near Kremasta (adapted from Snow (1972))

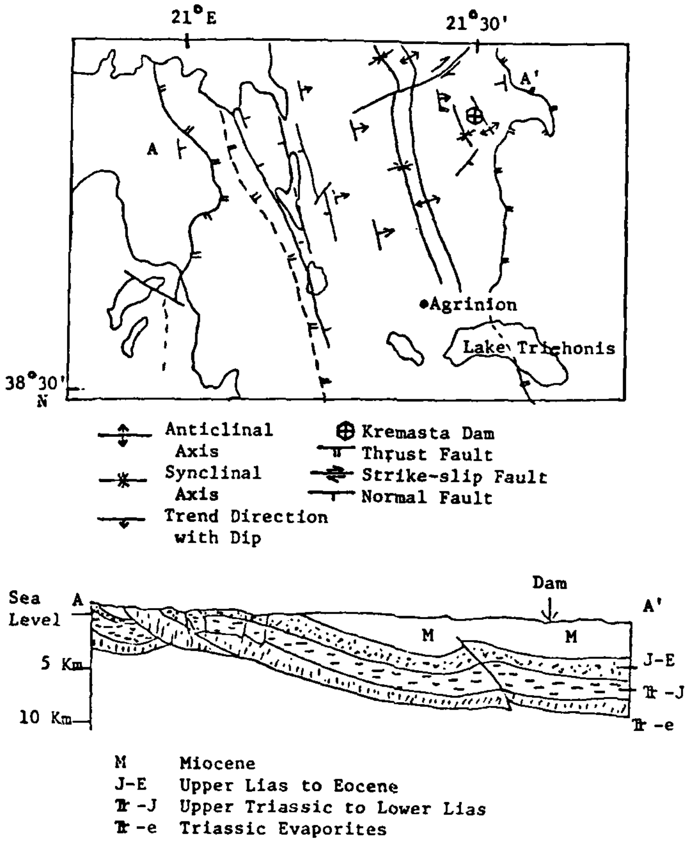


Figure 49. Geologic section of central Greece (adapted from Jenkins (1972))

the Acheloos River is a losing stream north of Smardacha and sometimes goes dry near Sivista. The groundwater flow is not predictable in karstic areas. It is assumed that the area of influence is extended due to these conditions and this increased area may include the northwest-trending fault along the Inochos River. This increased area is shown by a dashed line in Figure 48.

204. Snow mentions the effect of the reservoir on several streams, most of which are included in the area of influence. Prevenza spring, located 13 km downstream from the reservoir, is described by Snow. He states that the discharge measured in July 1965 before Kremasta filled was 71 ℓ/s and after filling was measured at 360 to 733 ℓ/s in January 1967. The natural variation in discharge prior to impoundment is

unreported. The zone of influence was extended to include Prevenza, as shown by the dotted line in Figure 48.

205. The region is one of great historical seismicity, although no historical earthquakes are reported in the area of influence of the reservoir. The historical record is drawn from Gutenberg and Richter (1954) and Rothe (1969) and is shown in Figure 50. The numbers assigned

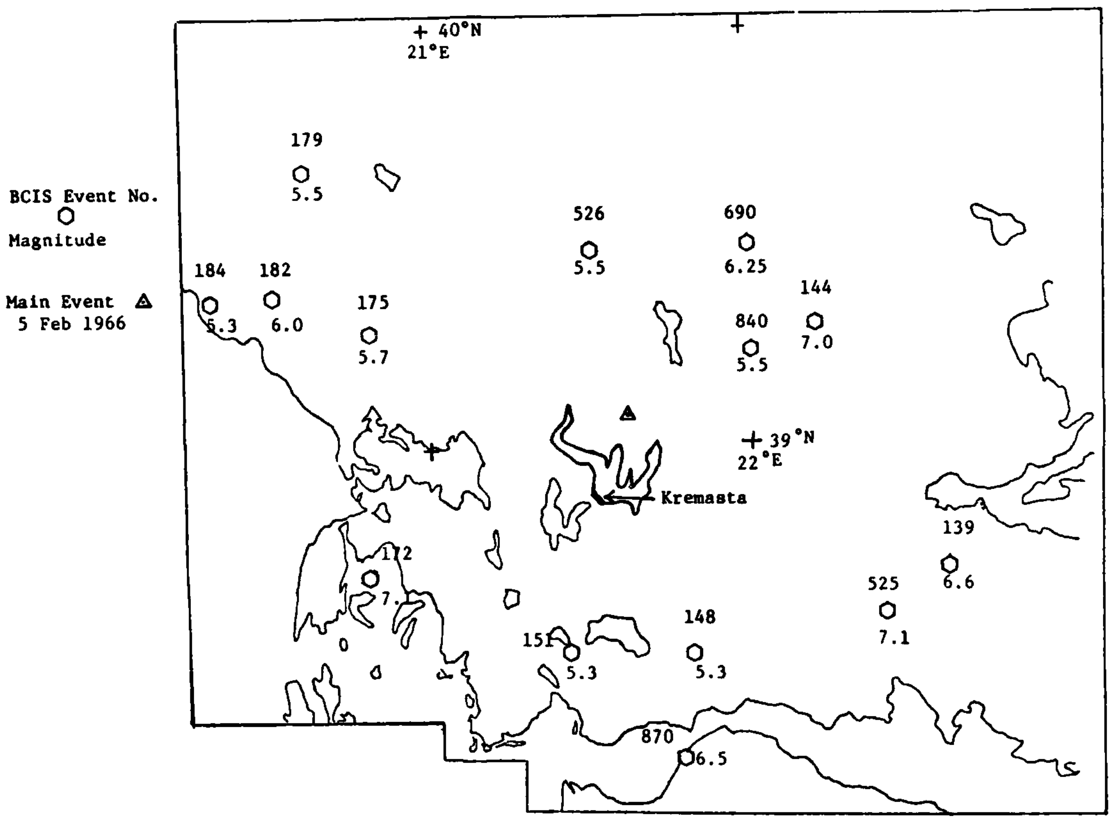


Figure 50. Historical seismicity, Kremasta

to the events are those reported by Gutenberg and Richter, and Rothe. The postimpoundment events are reported by Comninakis et al. (1968). The reports concerning preimpoundment reported in Gupta and Rastogi (1976) indicate that the Acheloos River area had never had events of magnitude > 6.0 from 1821 until reservoir impoundment. They further report that between 1965 and 1970 three events of magnitude > 6.0 occurred. Other than the event of 5 February 1966, no other event whose magnitude is greater than 6.0 occurred in the Acheloos River area (meaning the reservoir area of influence). A table of reported seismicity is shown as Table 15.

Table 15

Historical Earthquakes,

38.2°-39.7°N, 20.2°-22.4°E to 1979

No.	Date	Location		M_s	Remarks
		Lat., °N	Long., °E		
870	07/06/25	38.25	21.75	6.5	h = 120 km
840	08/15/32	39.25	22	5.5	h = 100 km
690	03/01/41	39.5	22	6.25	
148	03/04/53	38.5	21.8	5.3	
174	08/09/53	38.3	20.8	6.5	
173	08/11/53	38.3	20.8	6.8	
172	08/12/53	38.3	20.8	7.1	
171	08/12/53	38.3	20.8	6.0	
170	09/14/53	38.3	20.8	5.8	
169	10/21/53	38.3	20.8	6.5	
151	11/30/53	38.5	21.4	5.3	
168	12/28/53	38.3	20.8	6.3	
144	04/30/54	39.3	22.2	7.0	
184	02/04/58	39.4	20.3	<5.3	
182	11/05/60	39.4	20.5	6.0	h = 49
175	11/11/60	39.3	20.8	5.7	h = 43
526	03/17/63	39.5	21.5	5.3-5.8	h = 78
179	07/13/63	39.7	20.6	5.3-5.8	
525	03/31/65	38.6	22.4	7.1	h = 78
139	07/06/65	38.7	22.6	6.6	h = 28
--	02/05/66	39.1	21.6	6.3	h = 20-34
--	05/04/66	39.3	21.3	5.5	
--	10/29/66	38.8	21.0	6.0	
--	01/04/67	38.4	21.8	5.3	
--	01/04/67	38.2	22.1	M_L = 4.4	
--	05/01/67	39.7	21.3	6.4	h = 15
--	05/01/67	39.5	21.2	M_L = 5.0	
--	04/08/70	38.4	22.7	5.9	h = 7
--	04/19/71	39.0	20.5	4.8	
--	09/17/72	38.3	20.3	6.8	h = 33
--	10/30/72	38.3	20.4	M_L = 5.5	

Note: Impoundment begins during July 1965. First seasonal peak, May 1966.

206. In 1963 an event (No. 526) occurred near the Acheloos River about 73 km north of the Kremasta Dam. This event whose magnitude was between 5.3 and 5.8 is shown in Figure 50 along with the 5 February 1966 event. Reports of low magnitude, local events near the dam persisted from 1965 through 1972. Reports by Comninakis et al. (1968) and Therianos (1974) leave no doubt that low-magnitude seismicity is frequent near the reservoir.

207. Preimpoundment low magnitude events are presumed not to have occurred based on the reaction of the local inhabitants to apparent increased seismicity as reported by Comninakis et al. It should be noted that the reservoir area is located in one of the most sparsely settled areas of Greece. The area of influence is nearly confined to the administrative department of Evritania. The population density was under 80 persons per square mile in 1961, as shown in Figure 51.

208. The background seismicity of Greece is high enough that "felt" tremors in the reservoir area would not be a rare happening. For example, an earthquake that occurred on 5 April 1965 may have been felt at Kremasta. The intensity distribution reported by Ambraseys (1967) is shown in Figure 52. Therianos (1974) reported the number of shocks felt at the damsite between 1967 and 1972. He notes that many of these shocks were not felt 30 km from the damsite. Comninakis et al. (1968) reported that between 16-19 January 1966, seven shocks were felt at the damsite. Of these seven shocks only one appears to have been instrumentally recorded and larger than an M_L of 3.4. Two events with a magnitude $\geq$ 3.4 are reported by Comninakis et al. for 16-19 January, but only one is within 50 km of the damsite. All reports have suggested a very local and shallow focus nature of the damsite tremors. With this in mind, it is not obvious how these tremors are related to the 5 February 1966 event which took place approximately 12 km from the reservoir at a depth of 20 to 34 km. Considering the high natural seismicity of the area and the widespread distribution of the shocks reported by Comninakis and plotted in Figures 50, 53, and 54, there is insufficient evidence to conclude that the shock of 5 February 1966 was induced by the reservoir. This case is categorized as N.

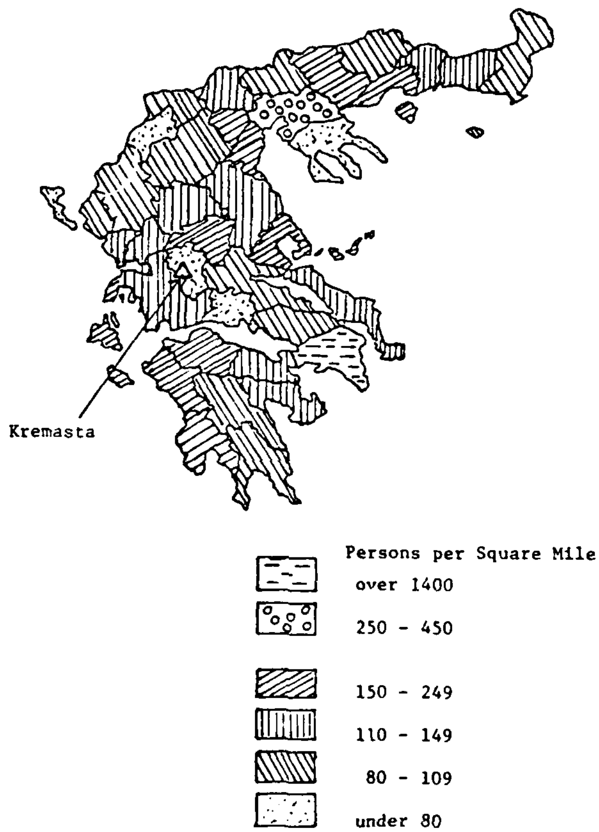


Figure 51. Population density of Greece, 1961 census

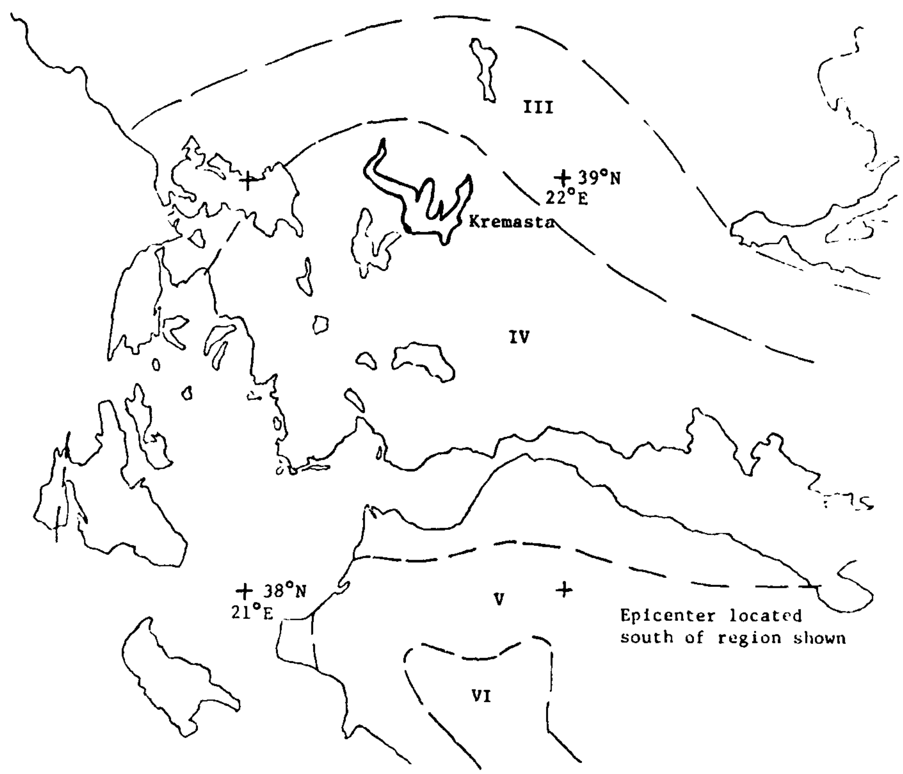


Figure 52. Intensity contours for megalopolis earthquakes (adapted from Ambraseys (1967))

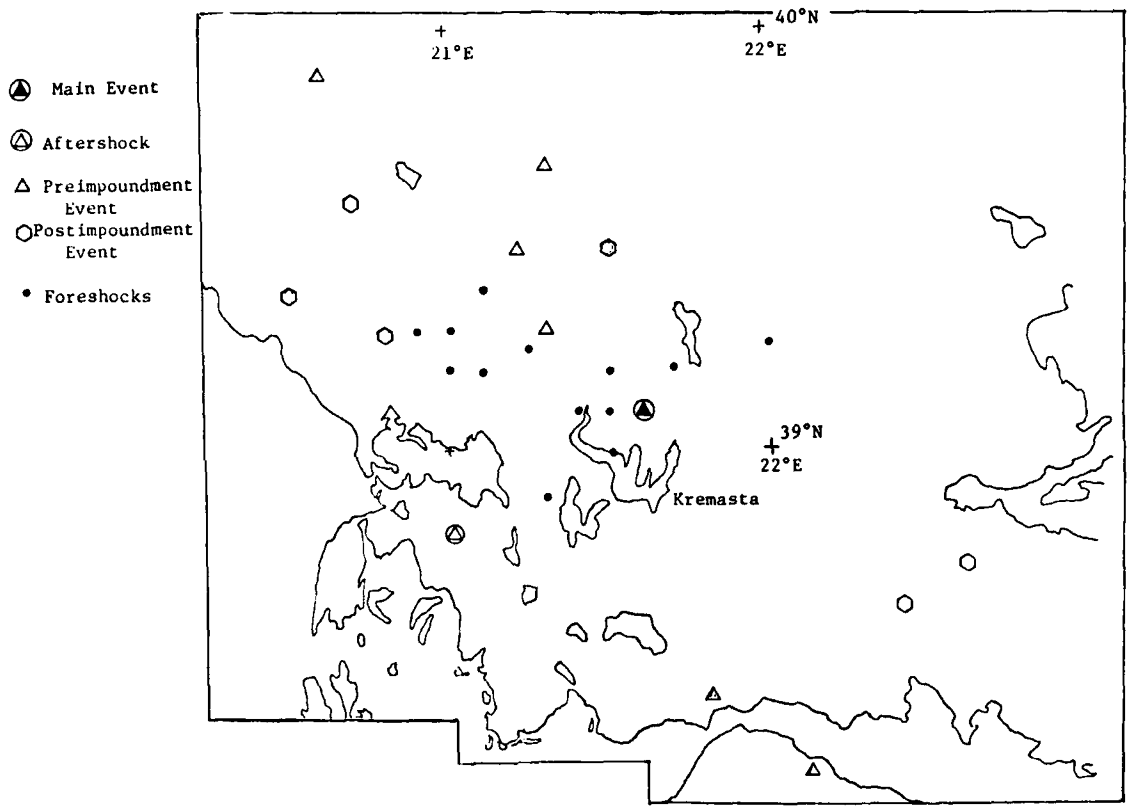


Figure 53. Earthquakes in central Greece, 1960-1970

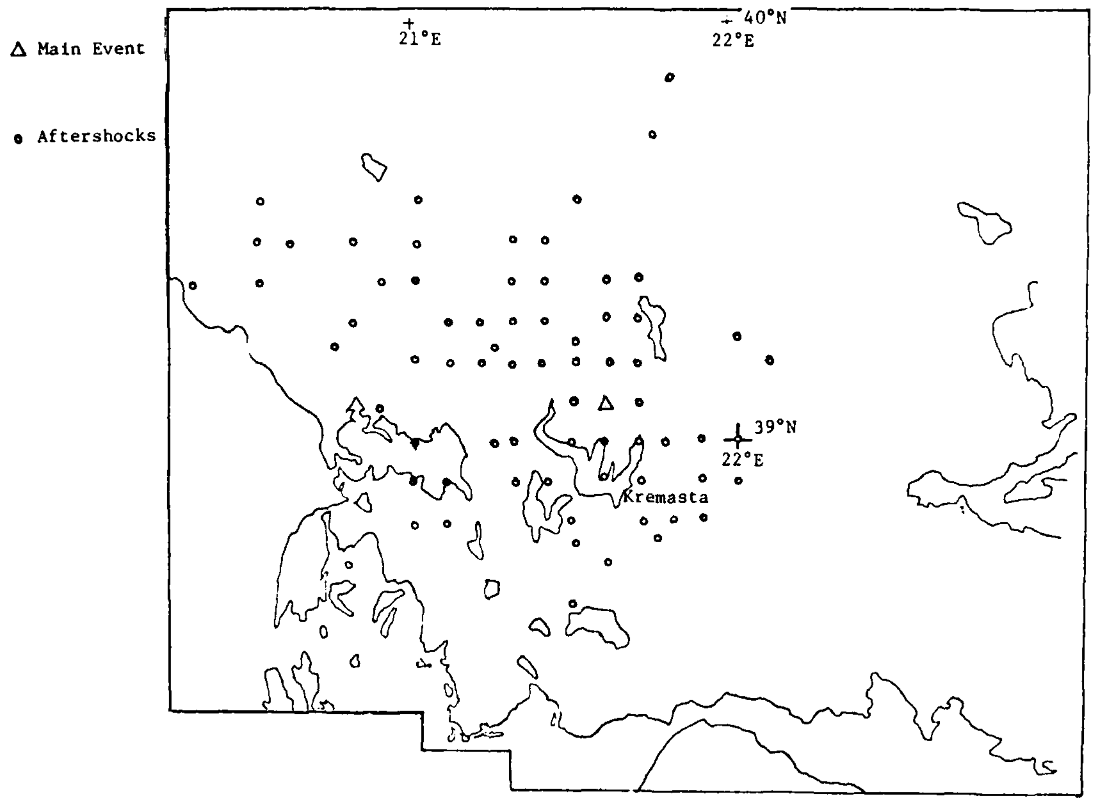


Figure 54. Earthquakes attributed to Kremasta

Correlation evidence--
original findings

209. The correlation evidence at Kremasta was collected by Comninakis and his associates. The reservoir variable selected was water level and the two seismic variables selected were number of shocks per 5-day period and the deformation per 5-day period. The data are shown in Figure 55. The correlation data were interpreted using an

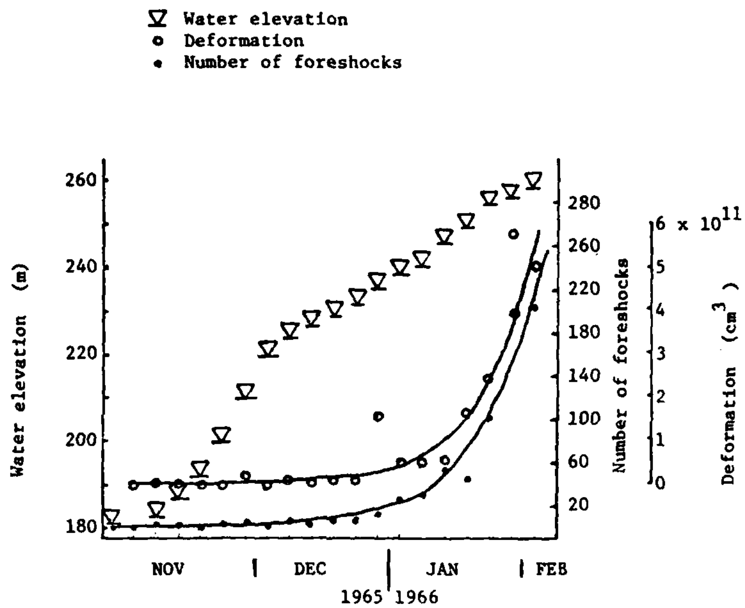


Figure 55. Correlation data, Kremasta (after Comninakis et al. (1968))

empirically based relationship between stress and rock failure. The empirical relationship was established by Mogi (1962), which is shown in Figure 56. Briefly stated, as stress increases linearly, strain and frequency of shocks increase exponentially. With reference to Figure 55, Comninakis et al. claimed that as the reservoir water level increased linearly between 4 December 1965 and 5 February 1966, the frequency of shocks and deformation increased almost exponentially. Comninakis states that "the qualitative resemblance between observational data and Mogi's experimental results is obvious."

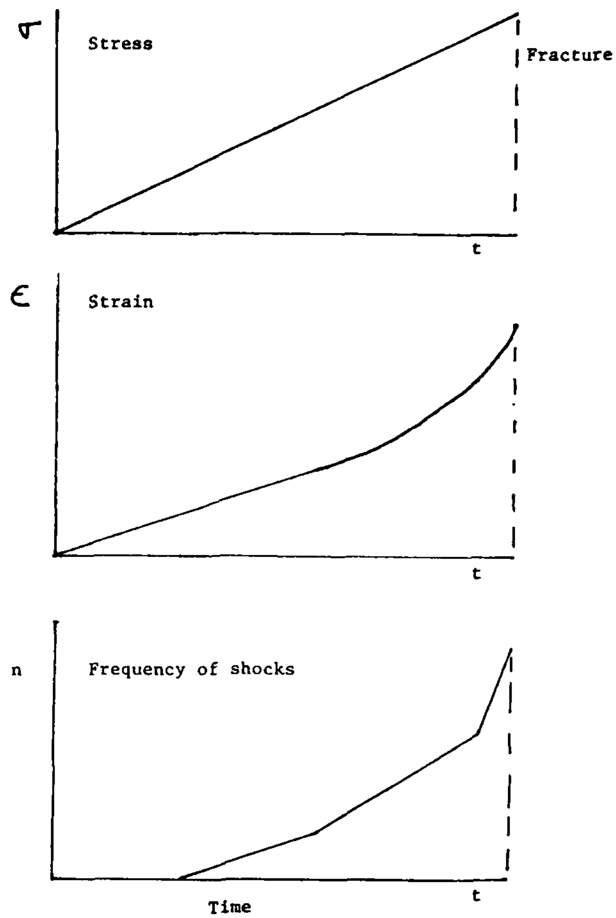


Figure 56. Relationships among stress, strain, and microfracturing (after Mogi (1962))

210. Mogi (1962) developed a theoretical expression for the transition probability of fracture. Together with experimental data he developed an expression relating log of the number of fractures per unit time to applied stress. Comninakis et al. determined that by analogy to the crust, the log of the number of shocks per unit time should have a linear relationship to the water level (Figure 57). The plot has a correlation coefficient of 0.98. The authors concluded that they have demonstrated that "a strong correlation exists between water loading and the occurrence of foreshocks." Their argument relies on several assumptions.

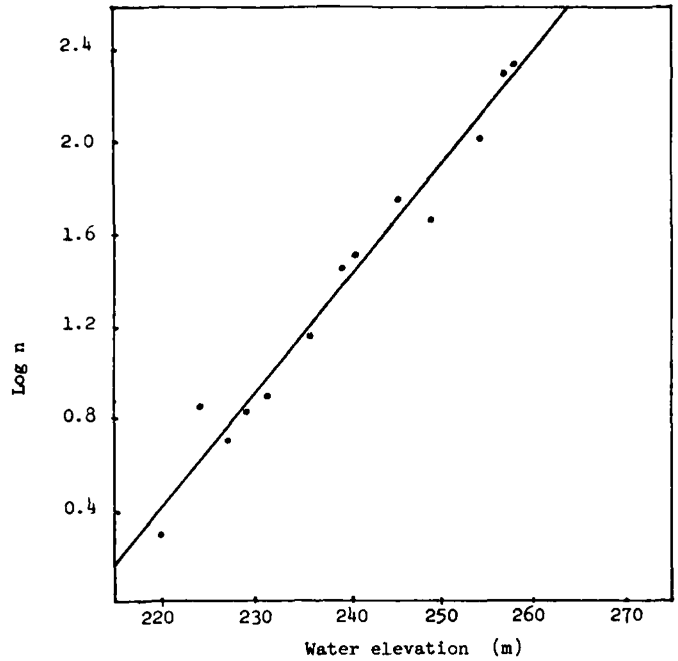


Figure 57. Relation between water elevation and number of shocks (after Comninakis et al. (1968))

211. The use of Mogi's work as verification of the relationship of water load to shocks requires that the correlation variables used be truly analogous to Mogi's variables. Mogi plotted applied stress, strain, and number of microfractures versus time. In Mogi's laboratory testing, the applied stress distribution, the physical specimen characteristics, and the sample dimensions are known. In the earth's crust the dimensions of the specimen and the applied stress distribution are not certain. The applied stress increase was linear over the wetted portion of the reservoir basin from 4 December 1965 to 5 February 1966. But that portion of the basin not under water on 4 December had a lesser increase in applied stress.

212. The area of the crust which should be considered as the loaded specimen is more uncertain. The locations of the foreshocks considered by Comninakis are shown in Figure 58. The foreshock groups are spread over a large area. The shocks of group 1 are more than 45 km from the dam and more than 25 km from the closest and shallowest portion

Figure 58. Foreshock groups, Kremasta (adapted from Snow (1972))

of the reservoir. The spatial relationship between the applied load and shock hypocenter cannot be ignored. They are 25 to 30 km from the main shock of 5 February 1966. If these shocks were removed from Figure 55, the plot would probably not resemble the results of Mogi. A complete catalog of events used to construct Figure 55 was not published.

213. A plot of deformation versus water level using the shocks ($M_L \geq 3.4$) located in the reservoir area is shown in Figure 59. The reservoir area is shown in Figure 58. Deformation was calculated using the procedure described in Comninakis et al. (1968). The located events cataloged in that reference were used as data in Figure 59.

214. In summary, the use of an empirically derived relationship

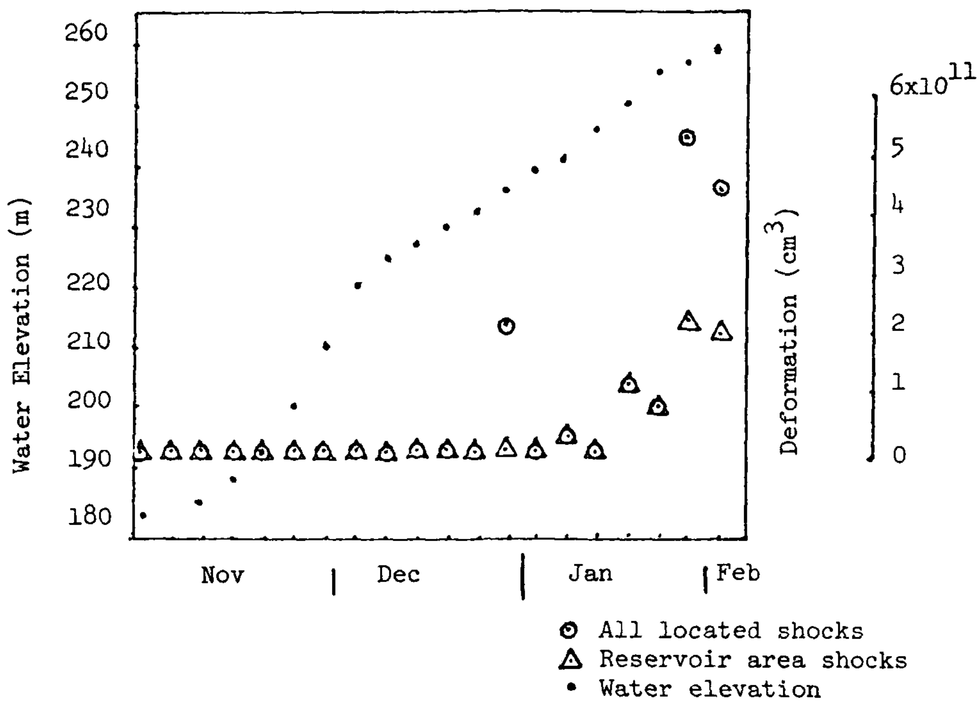


Figure 59. Relationship between water elevation and deformation (adapted from Comninakis et al. (1968))

to interpret the correlation evidence is a reasonable approach. This provided a conceptual framework in which to evaluate the meaning of the correlation. Difficulty arises in equating the laboratory variables with field variables. Water level is a very approximate measure of load. The field stress distribution is unknown and the spatial distribution of the shocks was not considered. The failure to make the field variable analogous to the laboratory variables weakens the conclusions drawn by Comninakis and his associates.

215. Another correlation for Kremasta was published by Therianos (1974). His data are shown in Figure 60. He gave no interpretation of the data. The information represents tremors felt at the damsite. There was no seismic instrumentation installed at the site during the period. He notes that most of the shocks have a local character in that many were not felt 30 km away in the town of Agrinion. The author did not indicate that he edited the data to remove large regional shocks

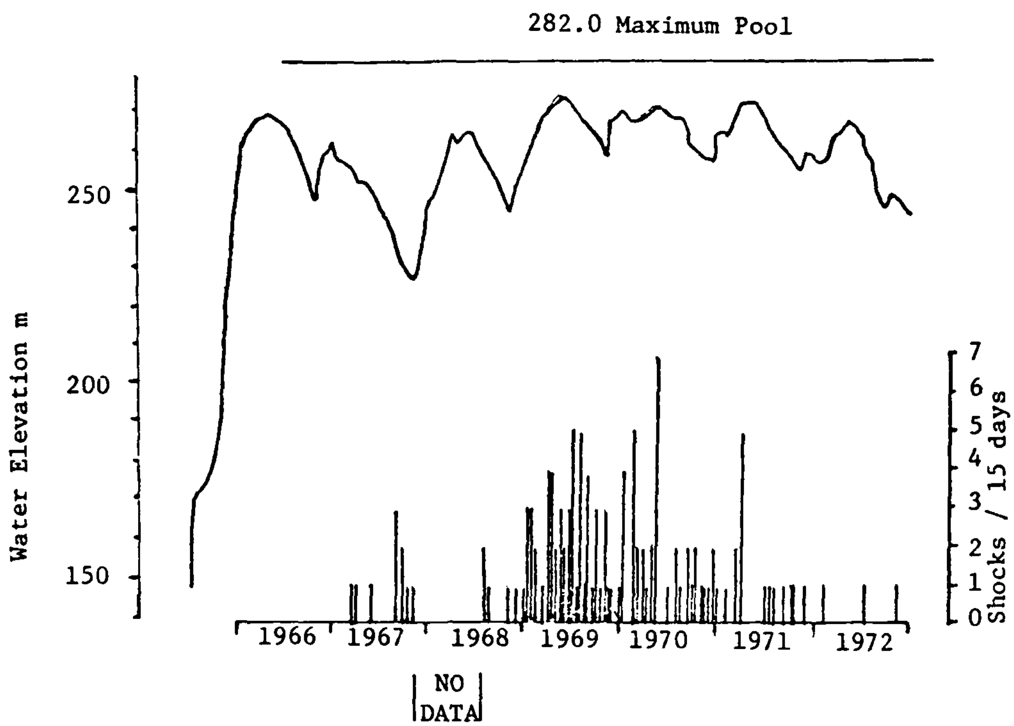


Figure 60. Correlation data, Kremasta, 1967-1972
(after Therianos (1974))

that may have occurred in central Greece but were felt at the site. A list of felt events occurring in the region is shown in Table 16. It appears that several regional shocks should have been felt at the dam. In particular the earthquake of 1 May 1967 was felt over a large area. The site should have been within the MMI V Contour. No shock is shown for that date in Therianos' data.

Correlation data--discussion

216. This case presents an extreme in that only a loading history is available for use as correlation data. Any events that occurred during the loading could possibly be triggered. The events recorded during the first filling are spread over a large area. The number of events whose epicenters are located within the reservoir drainage basin do appear to increase, but the same statement applies to those events remote from the reservoir. No conclusion can be drawn.

217. Another data source is the information provided by Therianos

Table 16

Felt Earthquakes, 1965-1973

Date	Location		Magnitude	Remarks
	Lat., °N	Long., °E	M	
03/31/65	38.6	22.4	7.1	h = 78 km
04/05/65	37.4	21.9	6.0	
07/06/65	38.7	22.6	6.6	h = 28 km
02/05/66*	39.1	21.6	6.3	Kremasta event
05/04/66*	39.3	21.3	5.5	
09/01/66	37.5	22.3	5.4	radius MMI V 110 km = 17 km
10/29/66*	38.8	21.0	6.0	
01/04/67	38.4	21.8	5.3	radius MMI V 80 km h = 17 km
01/04/67	38.2	22.1	m = 4.4	h = 44 km
02/09/67	39.9	20.3	5.7	radius MMI V 80 km
03/04/67	39.1	24.6	6.5-7.0	radius MMI V 70 km h = 60 km
03/04/67	39.0	24.7	M_L = 4.4	h = 35 km
05/01/67	39.5	21.2	M_L = 5.0	
05/01/67	39.7	21.3	5.75-6.0	radius MMI V 150 km h = 15-20
10/13/69	39.9	20.6	Ms = 6	radius MMI V 135 km
04/08/70	38.4	22.7	5.9	h = 7 km
04/19/71	39.0	20.5	4.8	
09/17/72	38.3	20.3	6.8	radius MMI V 280 km
10/30/72	38.3	20.4	M_L = 5.5	

Note: This is not intended as a complete catalog. Most of the information extracted from Seismological Notes section of the Bulletin of the Seismological Society of America.
* Shocks included in Comninakis' paper.

(1974). He provided data on felt events at the damsite recorded by Dr. K. F. Benko. These data were based on local shocks of undescribed size felt at the damsite. Larger shocks whose epicenters were tens of kilometres from the site could be represented as well as very small shocks which have a felt area of only a few kilometres. The data shown in Figure 60 are discontinuous but do provide information during unloading as well as loading. It is possible that small felt shocks which occurred near the epicenter of the 5 February 1966 event may have gone unfelt at the damsite some 25 km away. Conclusions drawn from these data do not apply to the large shock of 1966 because no epicenters are available.

218. It is difficult to assess the possibility of deep fluid communication. Since a portion of the reservoir is in karstic terrain and there are some thermal springs in the reservoir, deep fluid communication must be assumed. This is also a region of thrust faulting. In a thrust fault environment the vertical stress is assumed to be the minimum principal stress. An evaluation of stability state different from the state in a normal fault environment is required. Both thrust and normal faulting are found in the reservoir area. Without an understanding of principal stress orientation at the site it is impossible to assign a stability state and interpretation is impossible.

Koyna

Earthquake history

219. The Indian shield was regarded as an area of very low seismicity. In 1962 a high dam was impounded at Koyna, India. Mild tremors occurred and the magnitude of these events increased until 1967 when a magnitude 5.5 event occurred in September followed by a magnitude 6 event in December 1967. No local instrumentation was available until 1964. At Poona a Benioff seismometer had been in operation more than 12 years prior to impoundment. This is about 100 km from the damsite. Gupta and Rastogi (1976) state that an event of magnitude > 4.0 occurring at the Koyna site would have been recorded at Poona and would have

been felt at nearby villages. No events from Koyna were recorded at Poona prior to impoundment, while more than 50 events magnitude ≥ 4.0 have occurred at Koyna from 1962 to 1976. According to various Indian sources, no felt reports of earthquakes at Koyna are known for the 100 years prior to impoundment.

220. A recent review of Indian seismicity (Chandra 1977) indicates that Koyna lies within a coastal seismic belt that has experienced major earthquakes. A report by Cluff (1977) based on a visit to Koyna indicates that the ground fissures that occurred south of the project showed consistent left lateral displacement across several sets of old stone walls. One of the walls shows more displacement than could be attributed to the 1967 event. The implication is that the causative fault showing surface breakage for several kilometres is located south of the project. The Indian authorities, observing the same feature, claim that it is unrelated to the 1967 event. The meaning of this feature is critical to interpretation of this case. Almost all of the seismicity has occurred within 20 km of the dam, as shown in Figure 61. Based on this evidence, the postimpoundment seismicity for felt magnitude events is greater than preimpoundment seismicity. This case is assigned to category I.

Correlation data--original findings

221. The situation at Koyna is unusual in that the most severe events did not occur during the first filling. Koyna was impounded in 1962 and the first seasonal filling occurred in 1963. The first events occurred in 1962 and the seismicity persists to the present (1981). The lake had undergone four seasonal filling cycles when the first significant events ($M_L > 5$) occurred in 1967. In December 1967 a magnitude 6.5 event occurred, followed by a long aftershock sequence.

222. Guha et al. (1974) prepared a report for the Indian government in which they treated the data in a manner that recognized the seasonal fillings and tried to accommodate the clouding of the seismicity data by the aftershock sequence. They used a set of five plots to interpret the relationship between the reservoir and seismicity. The

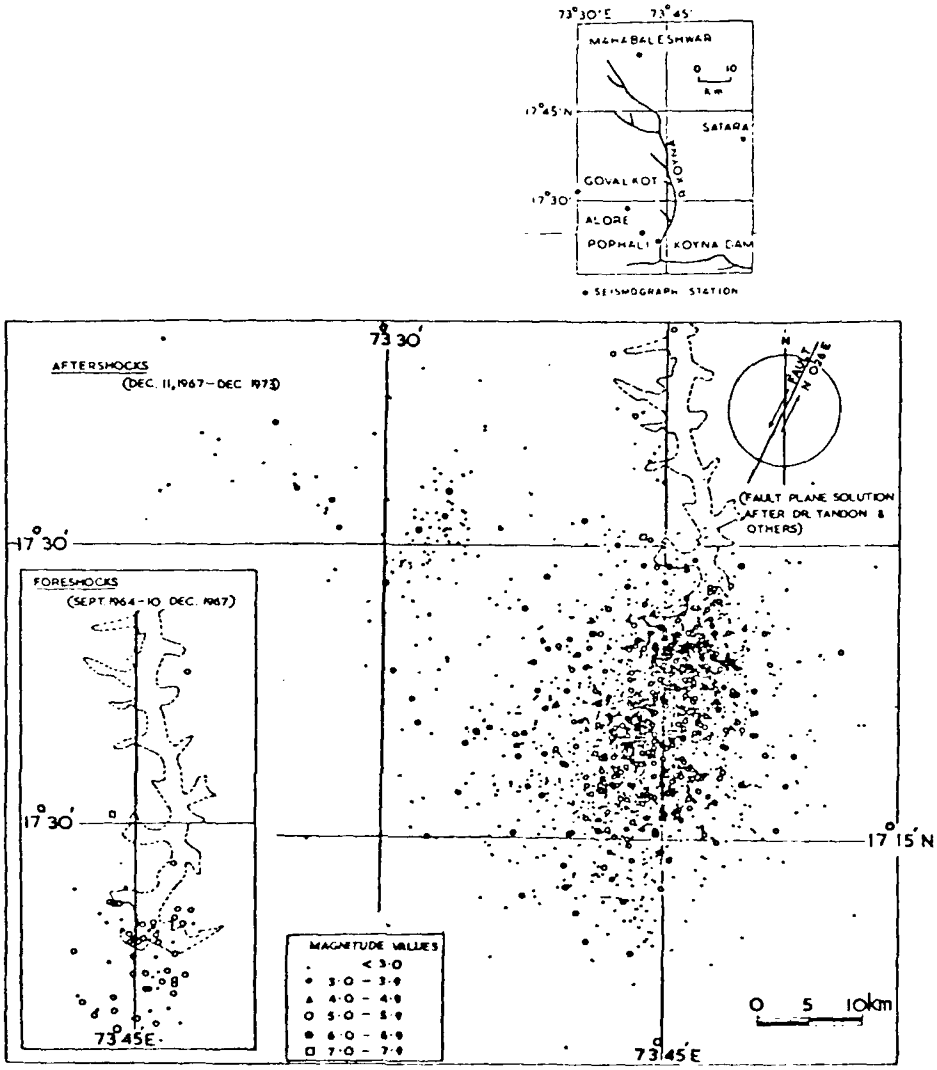


Figure 61. Koyna epicenters, 1964-1973
(after Guha et al. (1974))

interpretation used the statistical measure of a correlation coefficient and evidence drawn from a periodogram. Figure 62 shows a representative plot of the raw data. Reservoir variables are lake level and inflow hydrograph. Seismicity variables are numbers of events per week and log energy release per week. Before applying any statistical measures, Guha et al. used the 10 December 1967 event to separate the data into foreshocks and aftershocks. They then fitted a smooth exponential

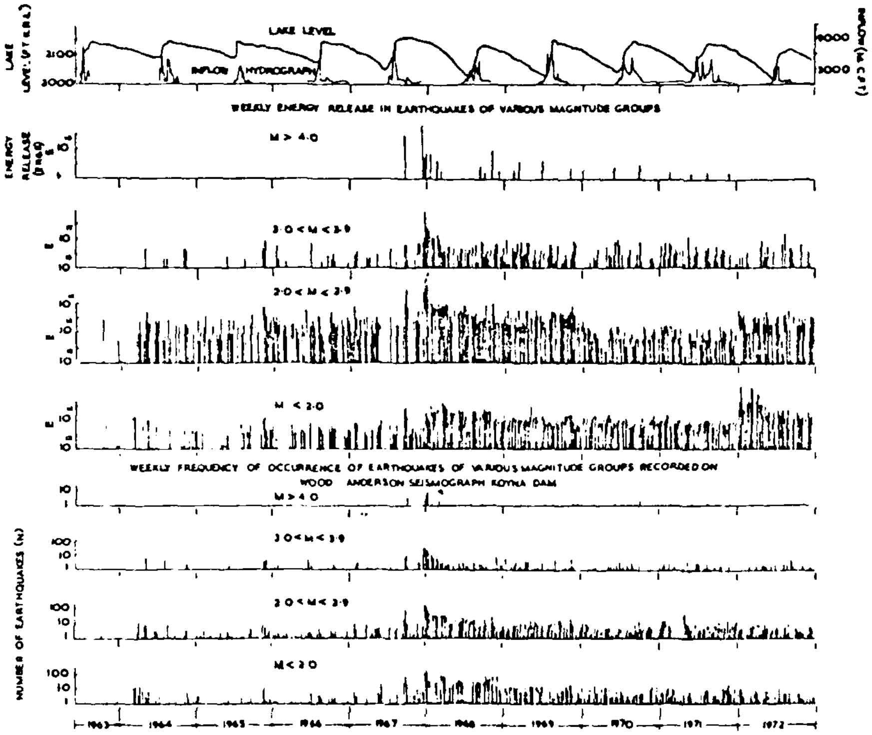
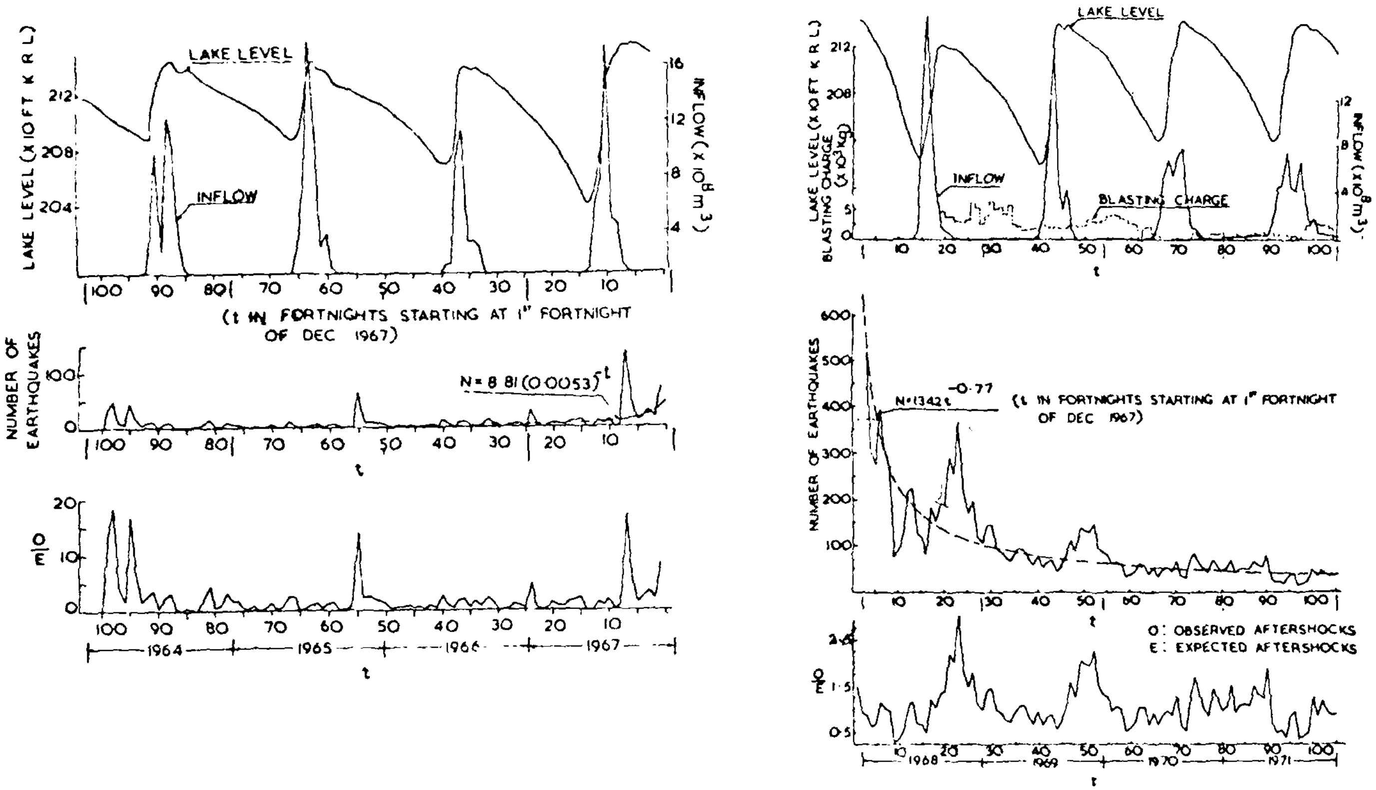


Figure 62. Correlation data, Koyna, 1963-1972
(after Guha et al. (1974))

relationship to the data. The fitted curves provided a value of the expected aftershocks or foreshocks. A new parameter for seismicity was then calculated as a deviation from these expected values. The observed values were labelled O , and expected values were labelled E . Two forms of deviations were used, O/E and O-E . An origin of 10 December 1967 was used on the time scale for the data plotted in Figures 63 and 64. The report contained a correlation for the O/E form of seismicity only. However, the authors stated that the best correlation had a value of 0.80 and was drawn from lake level versus the O-E form of aftershock data (1968-1971). They failed to show either the plot or the calculations but noted that the reservoir level data were used employing a time lag of 6 to 8 fortnights (3 to 4 months). The authors state that this explains about 60 percent of the data. The assumptions made by Guha et al. are not discussed in their report. The treatment of the data requires that several assumptions be met. Several of the most critical are:



Foreshocks

Aftershocks

Figure 63. Correlation data, Koyna, number of events (after Guha et al. (1974))

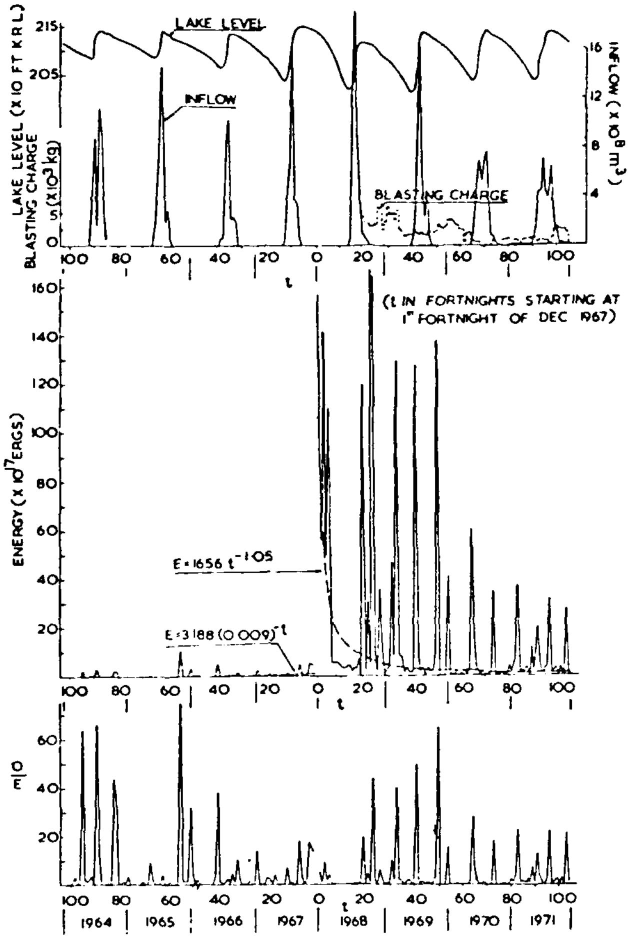


Figure 64. Correlation data, Koyna, energy (after Guha et al. (1974))

a. All of the events must be related to the 10 December 1967 event.

b. The temporal pattern of events can be fully described using fitted exponential expressions.

c. Deviations of observed values from these exponential expressions represent some modification of natural seismicity by some unknown agent.

The assumptions are discussed in the order in which they are listed above.

223. First, an examination of the epicenters shows that the seismicity is diffuse. If all seismicity were occurring on one fault, it

would be more reasonable to handle the seismicity as a single group. The seismicity is widespread and sources are very hard to identify. It is possible that portions of the foreshocks and aftershocks represent independent events and should be excluded from any curve fitting. Since separate sources are not apparent, all the earthquakes are considered to be related. This diffuse pattern may be real. Attempts have been made to improve the epicentral locations reported by Guha et al. (1974), but have failed to reduce the scatter and resulted in new but not improved locations.

224. Second, Guha et al. chose to represent the foreshock and aftershock sequences by smooth curves fitted to all data points. The expression used was the form $N(t) = Ce^{-pt}$ where C and p are constants. This expression can frequently be closely fitted to an aftershock series. No particular attributes are associated with C and p.

225. Omari (Utsu 1969) developed an expression in the form $N(t) = K/(t + c)$ to describe the aftershock sequence of the Mino Owari earthquake which occurred in central Japan in 1891. A modified Omari formula $N(t) = K/(t + c)^{-p}$ is commonly used to describe aftershock sequences. The expression selected by Guha et al. (1974) is one of several forms which are found in the literature. In fact, Guha et al. (1970) considered the use of the modified Omari formula for the Koyna data but since the local seismic network was put out of service for a half-day following the 10 December 1967 event, the constants for the modified Omari expression could not be determined and a simpler form $N(t) = D^{-t}$ was used. The form of the description of the aftershock sequence is arbitrary.

226. Third, deviations from the adopted fitted curve may represent a variety of conditions. It is not clear whether the data were edited to reflect the sensitivity of the seismic network. Stations were added at Pophali on 19 April 1968 and Alore on 19 July 1968. The station at Mahabaleshwar changed the sensitivity of the instruments on 20 July 1968 and again on 5 September 1968. On 10 September 1968 another station was added at the damsite. One year later in September 1969 the new Koyna damsite station increased sensitivity as did the station at Alore and an

additional instrument was installed at Pophali. The effects of the net changes are not addressed in Guha et al. (1974).

227. Along with the three assumptions previously mentioned, some additional assumptions must be made to qualify the use of a correlation coefficient. Again the text of Guha et al. (1974) does not elaborate on the calculation of the correlation coefficient. From his comment that the coefficient of 0.8 explained about 60 percent of the data it appears that Pearson's rho was used. To interpret Pearson's rho quantitatively, several distributional assumptions must be satisfied. Both variables, water level and seismicity, must come from normal populations. Two forms of seismicity data were used, O/E and O-E . All of the correlation figures shown by Guha used the O/E form, which is not likely to be normally distributed because of the way deviations are treated. When fewer events are observed than are expected, O/E takes on a value between 0 and 1. When more events occur than are expected, the value of O/E is at least one and is unbounded. In some of the figures, values of O/E are greater than 100. The form O-E has similar but less extreme difficulties. When fewer events are observed than expected, O-E ranges from -E to 0 . When more events are observed than expected, O-E is positive and unbounded. Although no O-E data are shown in the report, the authors state that the highest correlation coefficient was obtained using O-E data where the number of events per fortnight was correlated to lake level.

228. A delay of 6 to 8 fortnights was used to adjust the lake level data. The authors refer to lake level as "load." Lake level crudely approximates total load but better expresses maximum loading intensity. No justification is given for selection of a delay period. The only explanation for this practice is that the tester has concluded that the data peaks coincide prior to plotting the data. The proper value of the delay is assumed to be the value for which the highest correlation coefficient is obtained.

229. Seismicity data in the form O-E is used to plot periodograms. A periodogram, shown in Figure 65, is a set of data specially prepared in a manner such that natural periods in the data show up as

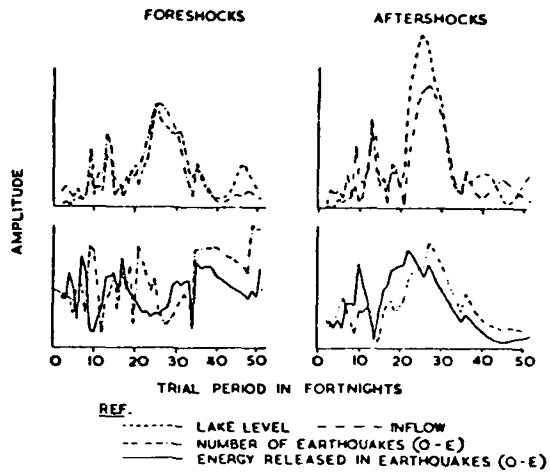


Figure 65. Periodogram data, Koyna
(after Guha et al. (1974))

peaks. The interpretation can be ambiguous since several peaks usually are present. Guha et al. conclude that the aftershock seismicity has a period between 20 and 30 fortnights and in his words "these earthquake residuals during 1968-1971 are largely influenced by water load fluctuations." They state that the conclusion does not hold for the foreshocks.

Correlation data--discussion

230. The seismicity at Koyna includes the largest magnitude event to be associated with a reservoir. This large event had many aftershocks, which are properly associated with the large event not with any reservoir parameter. The seismicity variable will be biased by the aftershocks. Without precise location data it is not feasible to try to remove aftershocks from the data. One possible way to remove many of the aftershocks is to look at only the events above a minimum magnitude of 3. The seismicity at Koyna appears very diffuse and much of the seismicity is located downstream of the dam. The hypocenters for many of the events were published in catalog form. Efforts were made to isolate sources, but the seismicity proved to be too diffuse to be partitioned.

231. The loading sequence of Koyna is unusual for reservoir-induced seismicity. The reservoir was filled in 1963 and went through four complete loading cycles before the large event of 10 December 1967.

The lake level was highest in 1965. A list of located events which occurred prior to the damaging event is given in Table 17. The reservoir rises abruptly each summer and gently declines until the following summer. The large events (M > 3) generally occur late in the year. Total stress is decreasing and load-induced pore pressures are dissipating.

232. The question of deep fluid communication is unresolved. Koyna is situated in flow basalt known as the Deccan Traps. The trap rock formation is about 1200 m thick near Koyna. The basalt flows are irregular and at the damsite seven flows have been mapped. Some of the flows have a weathered zone of red clay capping the flow. The clay layer should act as a barrier to fluid communication, but the layers may not be continuous. Athavale (1975) presents a host of indirect evidence for a line of faults, located immediately west of the watershed, which he claims are triggered by the increased pore pressure transmitted from the Koyna lake. A zone of hot springs runs parallel to the continental divide west of the watershed of the reservoir. Unlike Hoover Dam, where warm springs are within the dam foundation, the springs near Koyna are not found within the lake area.

233. There is conflicting evidence concerning the reaction of the springs to the reservoir level. The possibility of deep fluid communication cannot be ruled out. Assuming that the reservoir does raise pore pressures deep in the crust, there is a time lag operating. The elevation of the maximum water level is important, but the duration of the load also becomes important. In 1967 the maximum water level was similar to the level of prior years but the load remained high longer. This will allow fluid pressures to rise to higher levels than previously experienced. Since the duration of a time lag may be on the order of a year the stability state cannot be evaluated with confidence. It is likely that the stability state was becoming more unstable with time but only slightly so. During the first loading in 1963 the water level reached about 2145 ft and did not fall below about 2040 ft. This leaves about 100 ft of seasonal fluctuations which could raise pore pressures about 3 bars maximum.

Table 17

Koyna Events to December 10, 1967*

Date	Magnitude	Lat., °N	Long., °E	Depth, km
10/28/64	3.5	17 37.8	73 47.8	13.0
11/03/64	3.4	17 24.9	73 45.9	11.0
11/04/64	3.4	17 24.2	73 44.8	3.0
08/09/65	3.1	17 24.0	73 44.7	3.0
09/12/65	2.8	17 23.2	73 46.9	6.0
11/06/65	3.8	17 23.8	73 46.2	5.0
11/07/65	3.0	17 24.5	73 46.2	3.0
11/08/65	2.9	17 24.0	73 45.6	2.0
11/08/65	3.0	17 23.8	73 45.0	3.0
11/08/65	3.0	17 25.0	73 46.5	4.0
11/08/65	3.6	17 24.9	73 48.0	4.0
11/09/65	3.1	17 24.6	73 45.7	1.5
11/09/65	2.8	17 24.0	73 45.6	1.5
11/09/65	3.8	17 27.9	73 47.2	6.0
12/27/65	2.6	17 19.8	73 47.5	5.0
01/04/66	3.6	17 20.6	73 44.0	4.0
02/12/66	2.6	17 26.8	73 45.0	5.0
02/24/66	2.0	17 24.2	73 45.0	1.0
06/14/66	3.9	17 20.2	73 45.3	8.0
09/24/66	3.0	17 21.7	73 47.6	1.0
09/24/66	3.1	17 21.2	73 44.0	4.0
09/30/66	3.2	17 25.7	73 47.9	2.0
09/30/66	3.3	17 22.8	73 46.0	9.0
10/05/66	3.1	17 22.5	73 45.6	9.5
10/17/66	2.4	17 22.5	73 45.2	6.5
10/22/66	2.6	17 22.5	73 46.5	7.0
01/14/67	3.1	17 24.7	73 44.4	1.5
01/14/67	3.2	17 24.6	73 46.2	2.5
01/18/67	3.2	17 24.9	73 43.5	1.5
01/18/67	2.8	17 25.4	73 45.0	4.0
01/23/67	3.1	17 23.5	73 42.8	4.0
03/09/67	3.1	17 21.9	73 46.5	7.0
03/13/67	3.1	17 22.5	73 46.7	8.0
04/29/67	2.3	17 21.3	73 42.0	4.0
04/30/67	3.0	17 20.9	73 42.4	4.0
04/30/67	2.9	17 23.9	73 45.1	1.5
06/30/67	3.3	17 26.1	73 43.7	3.0
09/12/67	3.0	17 23.2	73 45.0	5.0
09/12/67	3.2	17 23.9	73 46.5	3.0
09/13/67	3.1	17 21.6	73 45.7	6.5
09/13/67	3.2	17 23.9	73 45.0	5.0

(Continued)

* From Guha et al. (1974).

Table 17 (Concluded)

Date	Magnitude	Lat., °N	Long., °E	Depth, km
09/13/67	3.2	17 25.0	73 47.6	1.5
09/13/67	3.2	17 29.2	73 45.4	5.0
09/14/67	2.5	17 25.2	73 44.3	5.0
09/15/67	2.8	17 25.4	73 43.2	1.5
09/15/67	2.8	17 24.6	73 46.5	6.5
09/15/67	2.9	17 26.6	73 41.8	3.0
09/16/67	2.6	17 24.9	73 43.5	6.0
09/22/67	2.3	17 23.4	73 46.2	3.0
10/07/67	2.8	17 38.9	73 46.4	11.0
10/24/67	2.9	17 21.0	73 39.3	5.0
11/04/67	3.3	17 20.7	73 46.7	1.0
11/08/67	3.5	17 23.4	73 47.0	3.0
11/08/67	3.2	17 26.0	73 44.2	1.5
11/09/67	2.8	17 24.4	73 44.7	3.0
11/09/67	2.2	17 26.7	73 44.6	1.5
11/16/67	3.5	17 26.9	73 51.1	4.5
11/18/67	2.7	17 25.0	73 45.4	3.0
11/21/67	3.2	17 24.4	73 44.7	4.5
12/01/67	3.5	17 23.1	73 47.2	6.5
12/01/67	3.1	17 21.6	73 45.7	3.0
12/01/67	3.1	17 22.4	73 45.0	4.0
12/01/67	3.0	17 25.6	73 47.3	3.0
12/02/67	2.1	17 25.7	73 48.1	2.5
12/02/67	3.2	17 25.5	73 46.0	2.5
12/02/67	3.1	17 22.4	73 45.7	3.0
12/04/67	2.8	17 24.0	73 47.0	7.0
12/08/67	3.1	17 22.4	73 47.4	2.5
12/09/67	2.8	17 22.0	73 47.2	8.0
12/09/67	2.4	17 20.4	73 45.9	1.5
12/09/67	2.8	17 19.0	73 46.5	4.0
12/09/67	3.2	17 23.1	73 43.8	5.0
12/09/67	3.0	17 20.2	73 45.0	14.5
12/10/67	3.8	17 24.1	73 45.1	14.5
12/10/67	3.2	17 20.0	73 46.3	22.5
12/10/67	7.0	17 30.5	73 45.8	12.0

234. In those cases where the lake level declines below the previous year's minimum, the crust should be becoming more stable until the water rises past the previous year's low. This was the case in June, July, and August 1966 and April through July 1967. During this first period only one located event occurred. The event had M_L equal to 3.9, was located south of the reservoir, and had an estimated focal depth of 8 km. During the second period only four located events occurred. They were all shallow (<4 km) and the largest had an M_L equal to 3.3.

235. After the main event of 10 December 1967 the aftershocks are so numerous that they bias the record for several years. The record after 1969 shows typical seasonal loadings. The maximum loading does not exceed those of prior years and the duration is unremarkable. If the tectonic stresses remained relatively stable, the crust should have seen no more instability than in prior years. The continued seismicity means that the events are either tectonic or reservoir-generated rather than triggered. The persistence of events up to magnitude 5 supports the tectonic nature of the events. Koyna is assigned to correlation category 0.

Kurobe

Earthquake history

236. Over the last 20 years Japan has extensively developed hydroelectric power projects. On the central island of Honshu, Kurobe Dam was constructed in the mountainous region known as the "Japanese Alps." The Kurobe IV project was begun in 1956. In August 1961, water level was about 100 m deep and may have been this deep for about 10 months. On 19 August 1961 a magnitude 4.9 earthquake occurred within 10 km of the dam. Several days later on 21 August a magnitude 4.0 event occurred at nearly the same location. Hagiwara and Ohtake (1972) report that no events had been reported by the Japan Meteorological Agency (JMA) in this region within 10 km of the dam. The records went back to 1926. This report is the only published evidence stating that the events of 19 and 21 August were induced by the reservoir. The decision to use 10 km as a provisional area of influence is not discussed by the authors. Their data are shown in Figure 66.

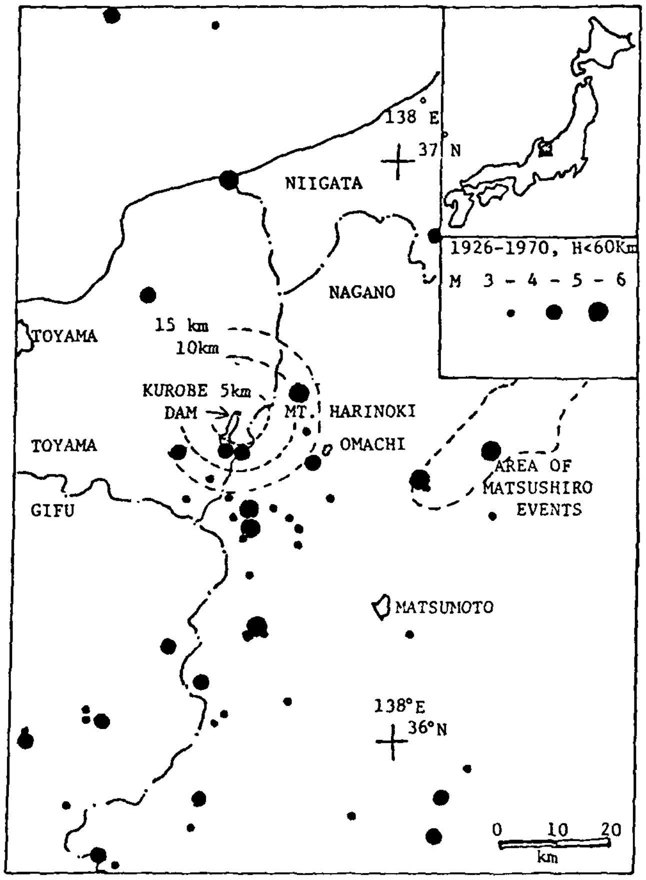


Figure 66. Historic earthquakes near Kurobe Dam (after Hagiwara and Ohtake (1972))

237. A selection of a 15-km radius would place four earthquakes in the vicinity of the dam prior to impoundment. One of these was a magnitude 6. A selection of 5 km would have no events in the vicinity of the dam through the present.

238. Japan is one of the few places in the world where instrumental data are available for the preimpoundment period. This is fortunate because the dam area is virtually uninhabited on a permanent basis and is the site of the Central Alpine National Park. The country is very rugged with cold winters where up to 10 ft of snow cover the ground 5 months of the year (Kansai Electric Power Co. 1957). The instrumental record is the only reliable source of preimpoundment seismic data. The

question that must be addressed is, "How reliable are the reports?" Also to be questioned is how large a magnitude will ensure detection. A study by Utsu (1961) provides some insight. Figure 67 shows the JMA

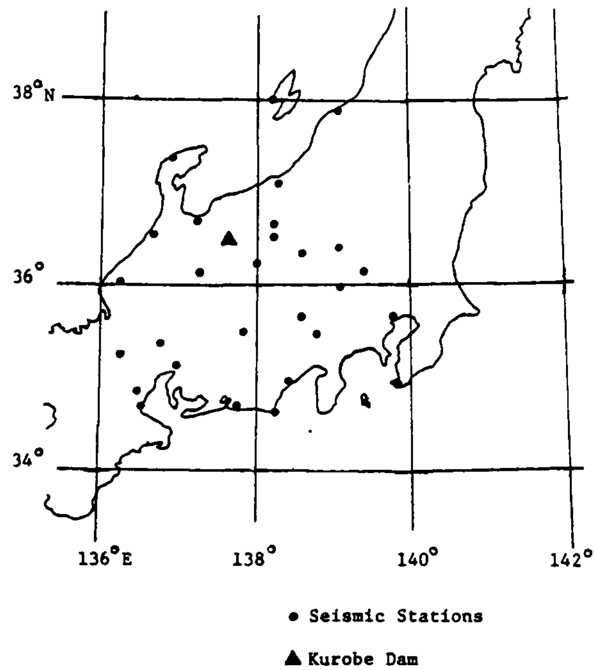


Figure 67. Seismic stations near Kurobe Dam (after Utsu (1961))

stations in the Kurobe area in 1961. The nearest station to the damsite is located about 44 km away at Toyama. Utsu presents data that indicate at a distance of 50 km JMA should detect all events above magnitude 3. For multiple station recording it seems that the minimum magnitude is about 3.5.

239. Once detected, how accurately can an event be located? A study by Aki (1963) dealt with the accuracy of location determined by JMA for the period 1960-1961. Fortunately for his study, the two largest events occurred during this period. The locations of these events as published by JMA were used by Hagiwara and Ohtake (1972) and are shown in Table 18. The travel time tables used to determine the locations by JMA in 1961 are now obsolete. Aki relocated the events based on improved tables and has estimated the errors in location for selected

Table 18

Kurobe Macroearthquakes

Date	Origin time (JST)			Epicenter		Depth	Magnitude
	hr	min	sec	Lat., °N	Long., °E	km	
1961, Aug 19*	22	24	11.8	36.500 ± 0.17	137.650 ± 0.017	00	4.9
Revised**	22	24	13.0	36.510 ± 0.077	137.656 ± 0.084	15.9 ± 30.1	4.9
1961, Aug 21	16	52	36.4	36.50	137.68	20	4.0
1968, Nov 16	07	25	28.6	36.52	137.65	10	3.8

* JMA gave error as 1 min.

** Aki (1963) gives this error for this particular event.

events. Although the revised location is only 1.25 km from the original location, the probable error for events near Kurobe Dam is large. The location of the 19 August event is given in Table 18 along with the estimated error in terms of degrees of latitude and longitude. In terms of kilometres the radius of error exceeds 7.5 km. This margin of error is for the 1960-1961 period. It seems reasonable that the error for earlier periods is at least as large. The location of the 1968 event may be accurate to within 1.5 km. The events occurred near the shallowest portion of the reservoir.

240. The reservoir had been used for power generation from October 1960, and the pool was approximately 100 m deep near the dam for almost 10 months when the events of August 1961 occurred. It should not matter greatly if the events occurred in July, August, or any other particular time. If the event is induced, it should be related to the pool depth near the time of occurrence. Presumably the pool depth was near the August level for almost 10 months prior to the event. The fact that the 4.9 event occurred on 19 August at 22:24 Japan Standard Time (JST) is curious. Less than 8 hr earlier a magnitude 7.2 earthquake occurred about 100 km from the damsite. The isoseismals of the event, known as the Kita Mino Earthquake, are shown in Figure 68. The intensity scale used in the figure is the JMA intensity scale. The region of Kurobe Dam experienced "rather strong" shaking. About 8 hr after the energy waves from the Kita Mino Earthquake passed through the Kurobe site the magnitude 4.9 event occurred. Was this event triggered by the reservoir? As always, nothing can be proved. The assertions made by Hagiwara and Ohtake would be much more impressive if it were not for the circumstances created by the Kita Mino Earthquake. The evidence of a postimpoundment increase of seismicity is clouded by the Kita Mino event and the accuracy of the locations of the events. Consequently, it is concluded that insufficient evidence exists to support the claim of increased postimpoundment seismicity and this case is categorized as N.

Correlation data--
original findings

241. In the correlation data presented by Hagiwara and Ohtake

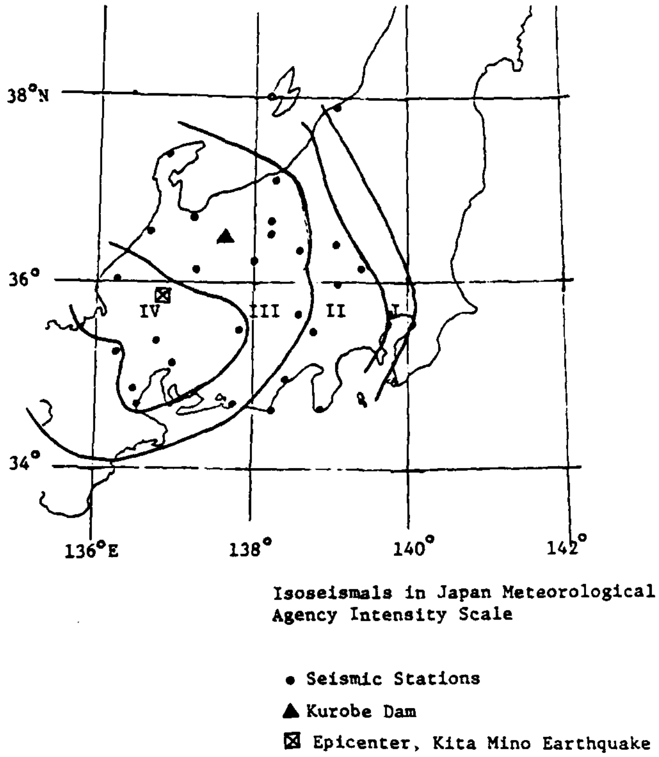


Figure 68. Isoseismal map of the Kita Mino earthquake (adapted from Hagiwara and Kayano (1961))

(1972) water level was the reservoir variable and the number of shocks per month was the seismic variable. The data for Kurobe is shown in Figure 69. Hagiwara and Ohtake comment on the visual association of the two curves and employ the second style of interpretation by using a cross correlation coefficient:

$$r_T = \frac{\sum\left[(N_i - N)(W_{i+T} - W_T)\right]}{\left[(N_i - \bar{N})^2 \sum (W_{i+T} - W_t)^2\right]^{1/2}}$$

This is Pearson's rho where a lag time T is permitted in the reservoir variable. The authors calculated r_T for the data in Figure 70. The largest value of r_T was obtained for a zero time lag. This value and a 95 percent confidence limit was estimated as $r = +0.41$, $+0.22 < r < +0.56$. The use of Pearson's rho and the calculation of confidence limits require that both variables be normally distributed. A

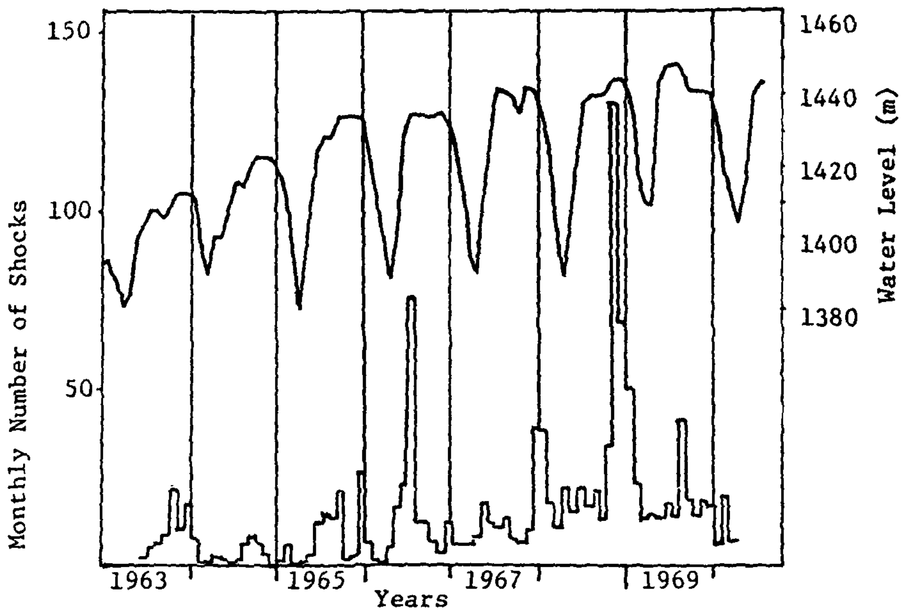


Figure 69. Correlation data, Kurobe (after Hagiwara and Ohtake (1972))

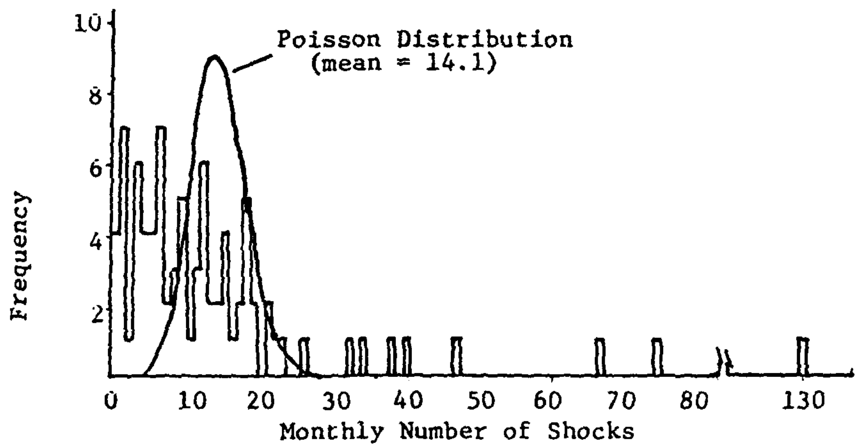


Figure 70. Distribution of monthly number of shocks, Kurobe (after Hagiwara and Ohtake (1972))

plot of the seismicity data is shown in Figure 70. The authors compared the distributions of the seismicity variable to the Poisson distribution and observed that the data were not Poisson-distributed. It is equally apparent that the data are not normally distributed. The authors describe the linear trend of the water level as $W_i(t) = 1408.5 + 34i$. They cite the correlation between the trend and seismicity as +0.34. Since the seismicity is not normally distributed, it would have been advisable to use a nonparametric correlation measure like Spearman's rho, or Kendall's tau. The authors conclude that "it is unquestionable that the occurrences of at least a considerable part of damsite shocks are due to the filling of the artificial lake."

Correlation data--discussion

242. Prior to completion of the dam there were no seismic instruments at the site. As a result, the correlation data available cover a period after first filling. Prior to the installation of instrumentation at the site, events could be detected by the JMA network. The detection capability was sufficient to record events down to magnitude 3. Very few felt events have occurred since impoundment. This case includes three principal events, two of which occurred in August 1961, and the other in November 1968. The near absence of macroseismicity makes this case of little engineering interest, but it is dealt with because of the allegation that Kurobe is a bona fide case of induced macroseismicity. The questionable details of the 1961 events have been discussed.

243. The reservoir goes through seasonal loading cycles and has had a gradual increase in the annual maximum water level each year. The water level increases rapidly each spring and declines each winter. The seismicity consists of microearthquakes. The locations were restricted to those events with S-P times equal to or less than 1 sec. This is approximately a circular area of approximate radius 8.5 km. This means the event could take place 8 km downstream and still be counted. No microearthquake data are available for the preimpoundment period. There is no evidence of deep fluid communication in this area. There are periods when the stress should be falling. The data show that periods of high water do contain increased seismicity but the same volume of crust

is cycled through approximately the same stress level. Each time the crust responds with microearthquakes. The events are either reservoir generated (not triggered) or related to cyclical tectonic stress change or some other cyclic variable. The temperature range at the site is severe. The events recorded took place more often at night than during the day. Hagiwara and Ohtake (1972) postulate that some atmospheric or temperature mechanism may be responsible for the events.

244. True induced seismicity should not respond well to statistical treatment. The data do not fit the Poisson assumption with a mean of 14.1. The data are skewed severely to the left and are closer to a negative exponential distribution. The use of a correlation coefficient that requires normality is not appropriate. If the events are reservoir generated, there is reason for a correlation.

245. The data were tested for independence of reservoir level and seismicity using Kendall's tau . This test assumes only that the data pairs each come from the same continuous population and each pair is independent. This latter assumption is not well met due to the continuity required by the water level data. There is a time ordering in the water level data. The value computed for tau is 0.37. If these parameters were independent, the expected value of tau would be zero.

246. There are geologic data that suggest that rainfall infiltration has a decided effect on stresses at the site. Calculations (Kansai Electric Power Co. 1967) of predicted thrust and displacement on the abutments of the dam do not compare well with measured displacements. The mountains that formed the abutments are said to "breathe." The movements of the mountain indicate that forces are at work that are not directly attributable to the reservoir. Kurobe is assigned to correlation category 0.

Manic 3

Earthquake history

247. Hydro-Quebec began the Manicouagan-Outardes hydroelectric project in 1959. Located north of the St. Lawrence River in eastern

Quebec, the project uses 19 dams to impound seven reservoirs on the Manicouagan and Aux-Outardes Rivers. Three of the reservoirs, Manic 3, Manic 5, and Outardes 4, are large reservoirs with dams over 100 m high. The area of the hydroelectric complex is vast.

248. The seismicity of the area is low to moderate (see Figure 71). At the southern terminus of the project, near Baie Comeau,

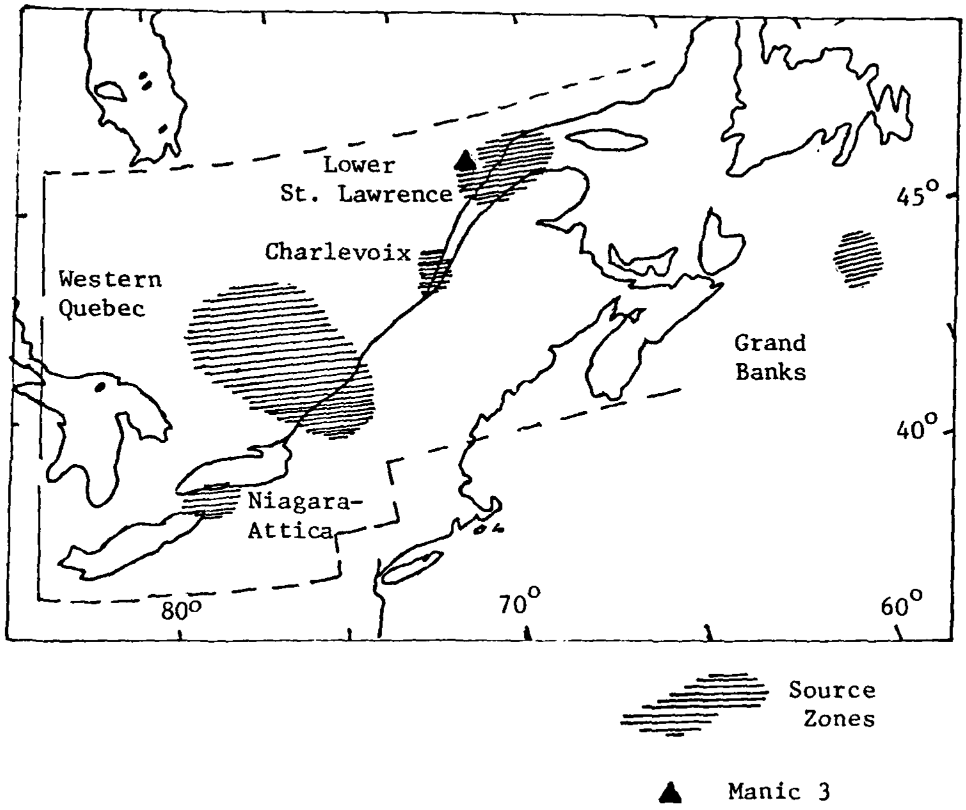


Figure 71. Earthquake zones in eastern Canada (adapted from Basham et al. (1979))

there is moderate seismicity associated with the St. Lawrence River valley. Proceeding north from Baie Comeau, the region becomes one of low seismicity. The Manic 3 dam is located at 49.8°N, 68.6°W. The historical seismicity of this region is listed in Table 19. A discussion of the seismicity of eastern Canada is given in Basham et al. (1979). Only events larger than magnitude 4 could have been recorded prior to 1963. This case is particularly unusual because special monitoring

Table 19

Historical Events (49°-50° N, 67.5°-69° W)

Date	Location Lat., °N	Location Long., °E	Magnitude M
06/12/17	49.0	68.0	4.0
05/17/38	49.0	68.0	4.0
06/23/44	49.4	67.8	5.0
10/21/58	49.2	68.5	4.0
10/23/75*	49.8	68.6	4.0

* Postimpoundment.

instrumentation was installed prior to impoundment, and the filling of Manic 3 was modified in response to observed seismicity. This is the only case known to the author with the exception of Nurek in the U.S.S.R., where there was management of the filling in response to observed seismicity. A detailed account is given in Leblanc and Anglin (1978). A summary is given here.

249. In December 1974, a monitoring station, MNQ, was installed to record events occurring in the project area (Figure 72). The instrument was capable of detecting events down to M < 1 in a 200-km radius. From January 1975 to mid-September 1975, no microearthquake activity was observed in the Manic 3 area. In mid-September some events were located near the Manic 3 area. The impoundment of Manic 3 began on 5 August 1975. During early October the events grew more frequent. On 20 October 1975 portable instruments were sent to Manic 3 to define the locations of the events. Three days later, a magnitude 4.1 event occurred in the Manic 3 reservoir. The portable instruments were not yet in operation, but the event was recorded on the Canadian Seismic Network and located very close to the dam. Within 5 hr of this shock the portable instruments were installed and recording the aftershocks. At the time of the occurrence of the magnitude 4.1 event there was no way of predicting the likelihood of future shocks or their magnitude. As a

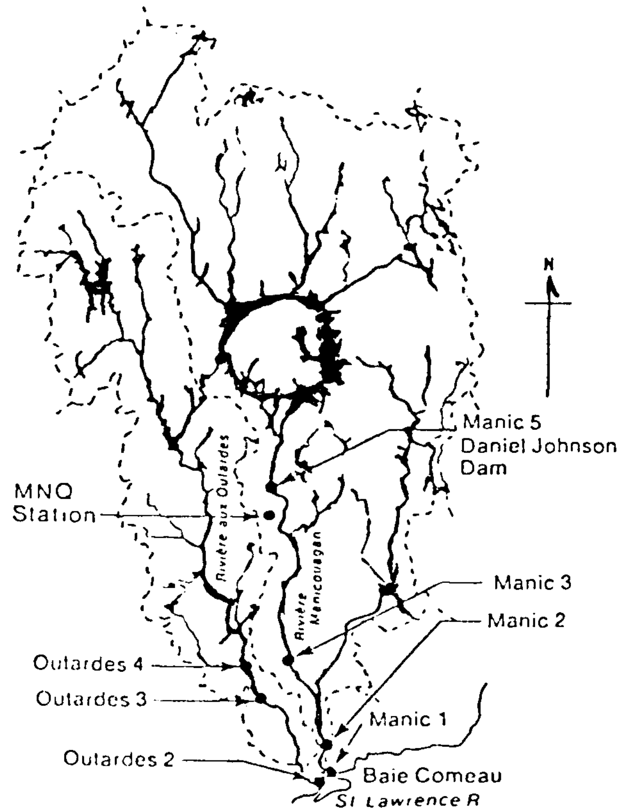


Figure 72. Manicouagan-Outardes project (after Leblanc and Anglin (1978))

precaution, filling was stopped for a few days and the damsite was inspected. Aftershock studies indicate that the events were located in a small area (20 km^2) centered on the reservoir about 8 km upstream of the dam. This is shown in Figure 73. Although the period of instrumental preimpoundment monitoring was short (8 months), complete detection of events near $M < 1$ was possible. The contrast in preimpoundment versus postimpoundment seismicity is shown in Figures 74 and 75. This case is categorized as I. Without the installation of instrumentation prior to impoundment the preimpoundment detection level would be near $M < 4.5$ and no increase in seismicity would be observed.

Correlation data--
original findings

250. Leblanc and Anglin (1978) present correlation evidence in

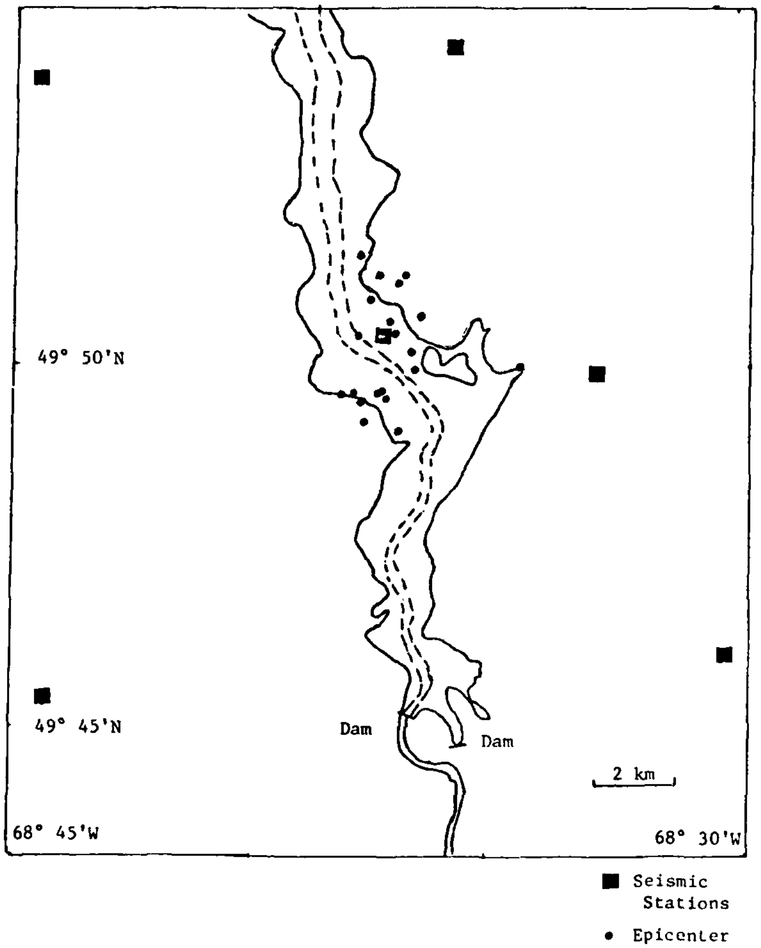


Figure 73. Epicenters at Manic 3 (after Leblanc and Anglin (1978))

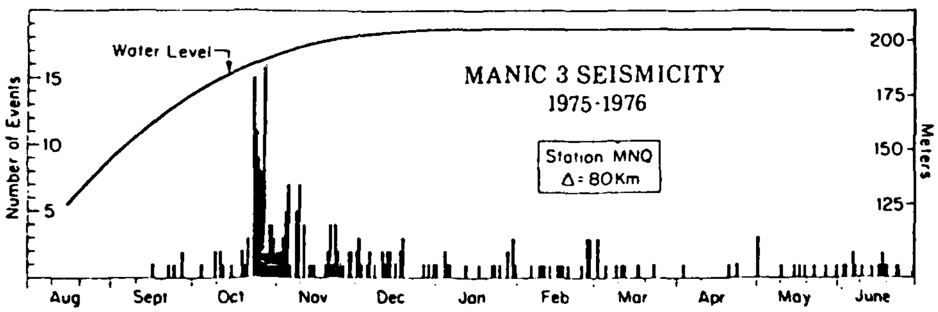


Figure 74. Correlation data, Manic 3, number of events (after Leblanc and Anglin (1978))

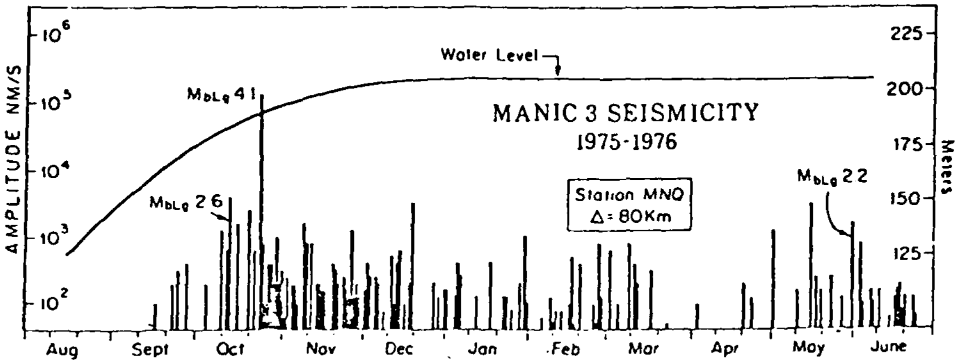


Figure 75. Correlation data, Manic 3, amplitude of largest event (after Leblanc and Anglin (1978))

the case of Manic 3, using water level as a reservoir variable and two seismicity parameters--number of events per day and amplitude of the largest daily event. They use the appearance style of interpretation where they note increases in both of their selected seismicity parameters with loading. Unlike the other cases it is impossible to align peaks in the curves since the water level rises smoothly and remains stationary at maximum water level. This unique feature occurs because the filling of Manic 3 was controlled by the discharge from the completed upstream Manic 5 dam. The authors concluded that the "coincidence in time of the seismic activity and the reservoir loading" taken along with data on focal depth and the aftershock sequence justify the consideration of Manic 3 as induced seismicity.

Correlation data--discussion

251. The data for this project include a period of preimpoundment monitoring that provides a sample of baseline data for the seismicity. This is particularly important in this case because of the unusual loading curve. No seismicity ($M > 1$) was detected in the reservoir area from January 1975 to mid-September 1975. The impoundment of the reservoir began during August 1975 and was completed by December 1975. While loading progressed, the reservoir area moved toward instability. Numbers of shallow events occurred in the reservoir area. The events are located offset from both sides of the reservoir as expected for a steep-walled canyon in a thrust environment. The region has high horizontal

stress as evidenced by the core discing that was observed. After loading was completed, the seismicity diminished substantially. This case is assigned to correlation category +.

Hsinfengkiang

Earthquake history

252. The source of preimpoundment information regarding Hsinfengkiang is found in Shen et al. (1974). In the 25 years prior to impoundment four felt events, Intensity V-VI, were reported. This is a well-populated area, unlike most of the other cases. One month after impoundment, instrumentally detected events were recorded for the reservoir area. It is assumed that felt shocks have a magnitude $M_s \geq 3.0$. Shen reports that 1 month after impounding felt shocks of $M_s \cong 2\text{-}3$ occurred near the reservoir. The reservoir area was instrumented in July 1961. The earthquake activity was located within 5 km of the reservoir. This is shown in Figure 76. An event $M_s = 6.1$ occurred in this area. The number of minor shocks with $M_s = 3.4$ was 5 to 6 per month in July and increased to 11 per month in February 1962. Using an average number of 5 events per month, this is an increase of felt events of 120 percent. This is the most radical change in seismicity recorded in any of the eight cases. This case is placed in Category I.

Correlation data--original findings

253. Shen et al. (1974) presented correlation data shown in Figure 77, using water level as the reservoir variable and the number of earthquakes per month and log energy release per month as the two seismicity variables. The data were interpreted visually by noting that a rapidly rising water level often precedes an increase in seismicity. The authors said there was a time lag between peaks in the water level and seismicity but no values were given. No mention is made of the quality of the correlation. After 1967 it is more difficult to see an association unless a variable delay time is postulated. The authors elaborate on the triggering mechanism and refer to particular water

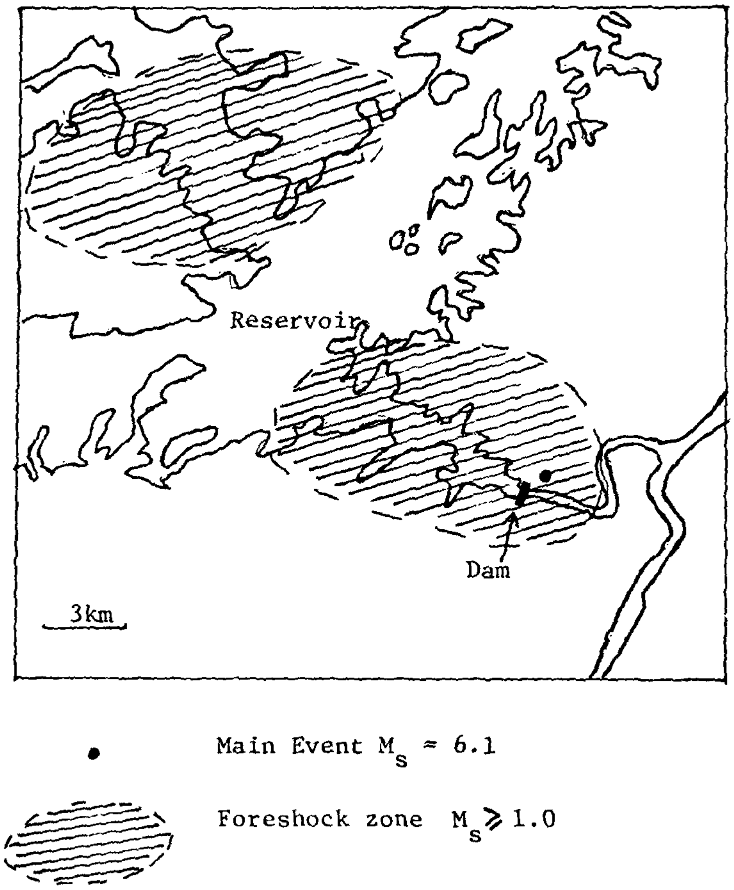
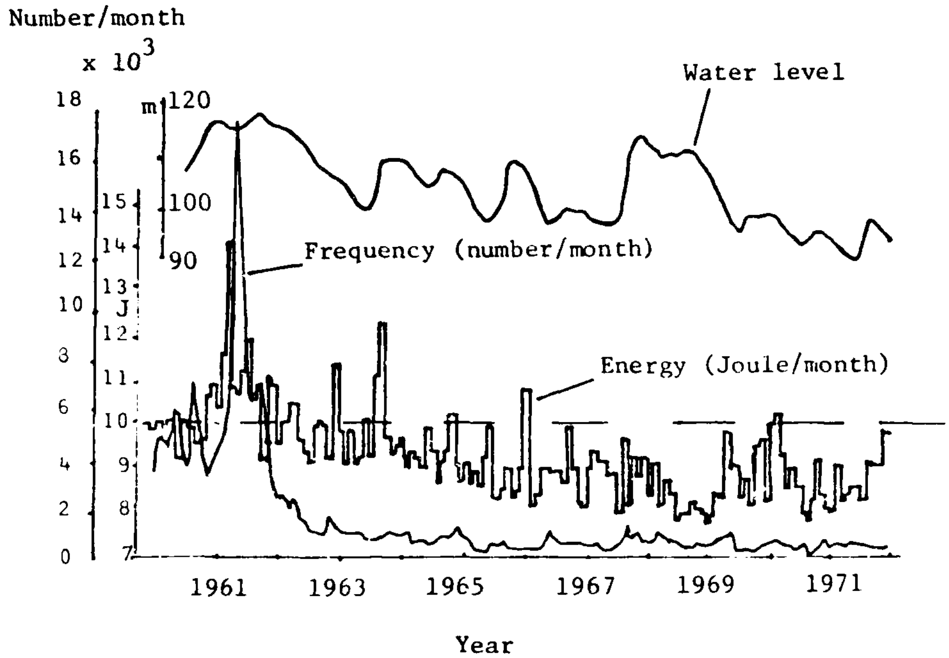


Figure 76. Earthquakes at Hsinfengkiang
(adapted from Shen et al. (1974))



Energy scale = Log Energy

Figure 77. Correlation data, Hsinfengkiang
(after Shen et al. (1974))

levels in discussing the seismic activity. The water levels referenced are below those shown on the correlation plot. The corre'‘tion data are not specifically used to draw conclusions regarding the likelihood of the reservoir triggering the activity.

<u>Correlation data--discussion</u>

254. The location data for seismic events at this site were collected after July 1961 during impoundment. Preimpoundment data indicate that four felt events took place in the preceding 25 years. The region is described by the Chinese as "unstable." This is interpreted by the writer as an indication that microearthquakes may have occurred prior to impoundment and gone unnoticed.

255. The seismic data used in a correlation should be screened to remove microearthquakes. The water level data along with instrumentally gathered seismic data are shown in Figure 77. The data in this figure can be used to approximately remove the microevents by moving the baseline to 10^{10} J.

256. There is little published data on which to evaluate deep fluid communication. Warm springs occur at some unidentified location so it cannot be ruled out. The stability was certainly decreased from October 1959 to late 1963. During late 1963, an increase in seismicity not due to the reservoir occurred. During mid-1964 the level of the reservoir was raised again accompanied by an increase of seismicity which included a magnitude 5.3 (M_s) event. During 1967 the lake level was relatively low for the entire year. In mid-1968 the lake level rose abruptly and remained high for about a year. No increase in seismicity was noted. After mid-1969 the lake level fell and assumed a lower level for several years. After 1965 nearly all the events were located in the narrow canyon near the dam. This seismicity is uncorrelated with the reservoir after 1965.

257. The continuing seismicity indicates the characteristic instability of the region. This case could be reservoir-triggered release of tectonic stress. The continuing seismicity may be purely tectonic or generated, but the reservoir loading influenced the time of occurrence of the large events in 1962 and 1964. Assign this case to correlation category +.

Nurek

Earthquake history

258. An experiment in reservoir-induced seismicity is taking place in Soviet Central Asia. Nurek Dam is a 315-m-high earth-fill dam, making it the highest dam in the world. The dam is located on the Vakhish River in Central Tadyikistan. Because of high seismicity the area has been studied since the 1930's. Detailed studies began in 1955 when a high sensitivity network was installed. By the mid-1960's, events of approximately magnitude 1.7 could be located throughout the region to within 5 km.

259. To identify the changes in seismicity due to the reservoir an area of influence, called by the Soviet investigators the "reservoir region," was selected. The area included about 2500 km within 17.5 km of the reservoir axis. Within this area it is believed that all

earthquakes equal to or greater than magnitude 1.7 (Soviet energy class K = 7) are detected.

260. Impoundment began in 1967, but the first substantial increase in water level began in 1971. From 1960 to 1971 the average number of earthquakes per 3-month period was 26. In 1971 the average increased to over 40 and in the last quarter of 1972 to 133 events. This set of data is shown in Figure 78. Tabularized data estimated from the

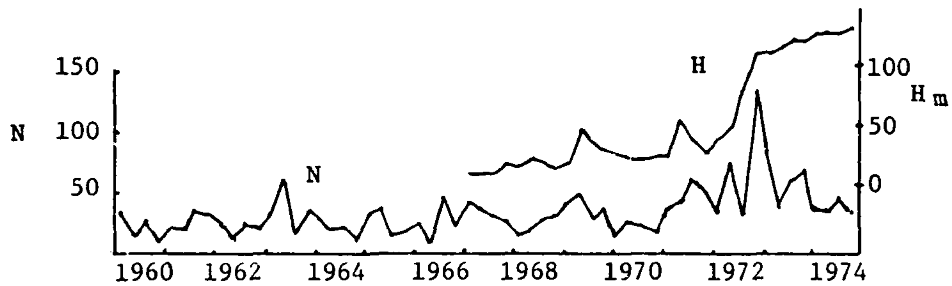


Figure 78. Correlation data, Nurek, 1960-1974
(after Soboleva and Mamadaliev (1976))

figure are shown in Table 20. Since the data are complete and reasonably accurate, considering the accuracy for epicentral location and the detection level, a statistical test can be employed. A two-sample Wilcoxon test was performed on the data to test the null hypothesis that the median 3-month average before impoundment is the same after impoundment. The alternate hypothesis is that the postimpoundment median is larger. Note that this test requires only that the data come from the same continuous distribution. It need not be normally distributed. The null hypothesis is rejected at a 99 percent level of confidence (P value = 0.0003). There is a postimpoundment increase in seismicity, and this reservoir is assigned to category I.

Correlation data--
original findings

261. The study of seismicity in the vicinity of the Nurek project in Soviet Central Asia has been pursued by an international team of American and Soviet scientists. The collection of data has been a team effort. The results of the study have been published both by individual

Table 20

Nurek - Number of Earthquakes (K $\geq$ 7) per Quarter

Year	First Quarter	Second Quarter	Third Quarter	Fourth Quarter
		Preimpoundment		
1960	33	13	26	12
1961	16	17	35	31
1962	23	14	24	23
1963	30	61	16	35
1964	27	21	23	11
1965	32	37	15	20
1966	24	8	48	20
		Postimpoundment		
1967	45	35	30	25
1968	12	17	25	29
1969	39	50	25	36
1970	13	25	22	19
1971	34	41	60	51
1972	33	73	32	133
1973	85	36	57	67
1974	36	34	47	33

members of the team and as collaborative efforts of several team members. Two sources of information will be referenced here. One is an article by Soboleva and Mamadaliev (1976) and the other by Simpson and Negmatullaev (1978). Since the data were developed jointly, only the more recent data will be mentioned.

262. Figure 79 is a plot of the correlation data to 1977. The reservoir variable is the water level and two seismic variables are the number of events per 10 days and the strain release per 10 days. These data were interpreted by Simpson and Negmatullaev (1978) using a theory which relates the change in water level to stability. Briefly stated,

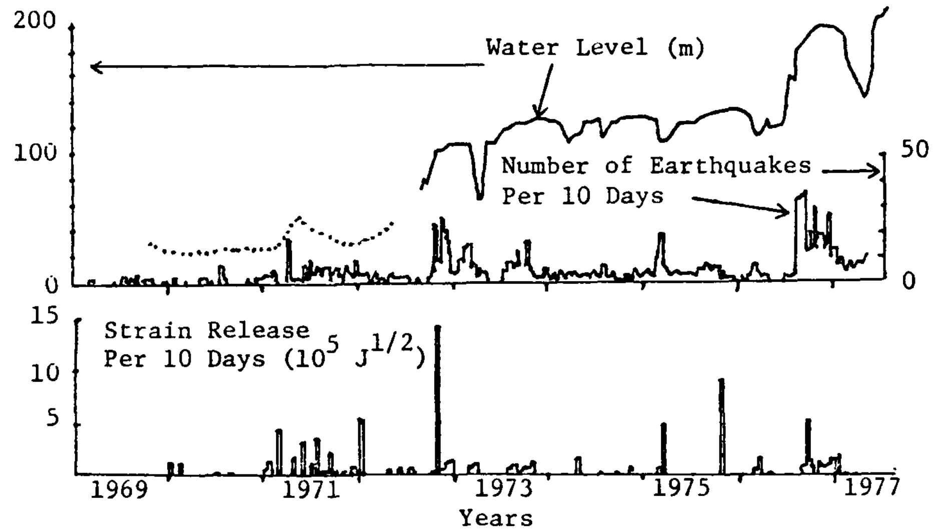


Figure 79. Correlation data, Nurek, 1969-1977
(after Simpson and Negmatullaev (1978))

the water level represents two parameters, load and pore pressure. The load component acts without a time delay; the pore pressure component acts with some unknown delay. The load component can either stabilize a region or move a region toward failure, depending on the direction of the principal stresses. An increase in the pore pressure component always moves an area toward failure. Nurek is in a thrust environment where the maximum principal stress is horizontal and the minimum principal stress is vertical. The load component of water level acts to increase the vertical stress and is a stabilizing influence at Nurek. An increase in the water level will act immediately to stabilize the region, but in time the pore pressure increase is transmitted to depth and moves the region toward instability. During unloading, the reduction in load acts to immediately destabilize the region and in time a pore pressure reduction will act to stabilize the region. The correlation data were interpreted in this framework.

263. The danger of this type of interpretation lies in the potential for bias by the interpreter. The data are often ambiguous. The interpreter may give undue consideration to features of the data which support his theory and ignore or discount features that conflict with

his notions. Simpson and Negmatullaev maintain that the data support the theory based on the data in Figure 79. An increase in water level prompts a decrease in seismicity, followed by an increase as the pore pressure rises. Specifically, the large earthquakes in November 1972 are related to the abrupt stop in filling at a depth of 100 m. In March 1975 the water level dropped sharply, giving an abrupt rise in seismic activity. In 1974 the water level dropped slowly enough to give the pore pressure time to dissipate so that no increase in earthquakes occurred. Based on these observations, the 1976-77 loading cycle was controlled to take place as smoothly as possible. This was done except in August 1976 when an outlet tunnel was tested which caused a rapid 3-m change in water level when the depth was near 160 m. This abrupt change initiated a burst of seismic activity.

Correlation data--discussion

264. The seismic monitoring at Nurek was begun years before the reservoir was impounded. The regional location of the events is shown in Figure 80. Based on the data published for 1964, 1965, and 1966, there are two general zones of seismicity within the proposed reservoir. These are labelled A and B in Figure 80. These zones occur along the same fault. A portion of this active fault appeared quiet during these three years and is labelled zone C. There was an increase in activity in zone B in 1969 during a rise in the water level from 20 to almost 50 m. This increase is contrary to earlier ideas that much greater depths (100 m) are required. This demonstrates that the amount of reservoir influence necessary to trigger events is relative to the state of "preparedness" of the fault. The water level remained stable until early 1971. Note that zone B in 1970 resembled the 1968 and 1966 pattern. In 1971 the water level was raised to 60 m and was accompanied by a general increase in seismicity along the fault. The water level was raised in the fall of 1972 and was accompanied by an increase in seismicity in the formerly quiet zones C and B. The water level dropped sharply in the spring of 1973 and was abruptly raised. The seismicity in zones B and C were again elevated. This case is assigned to correlation category +.

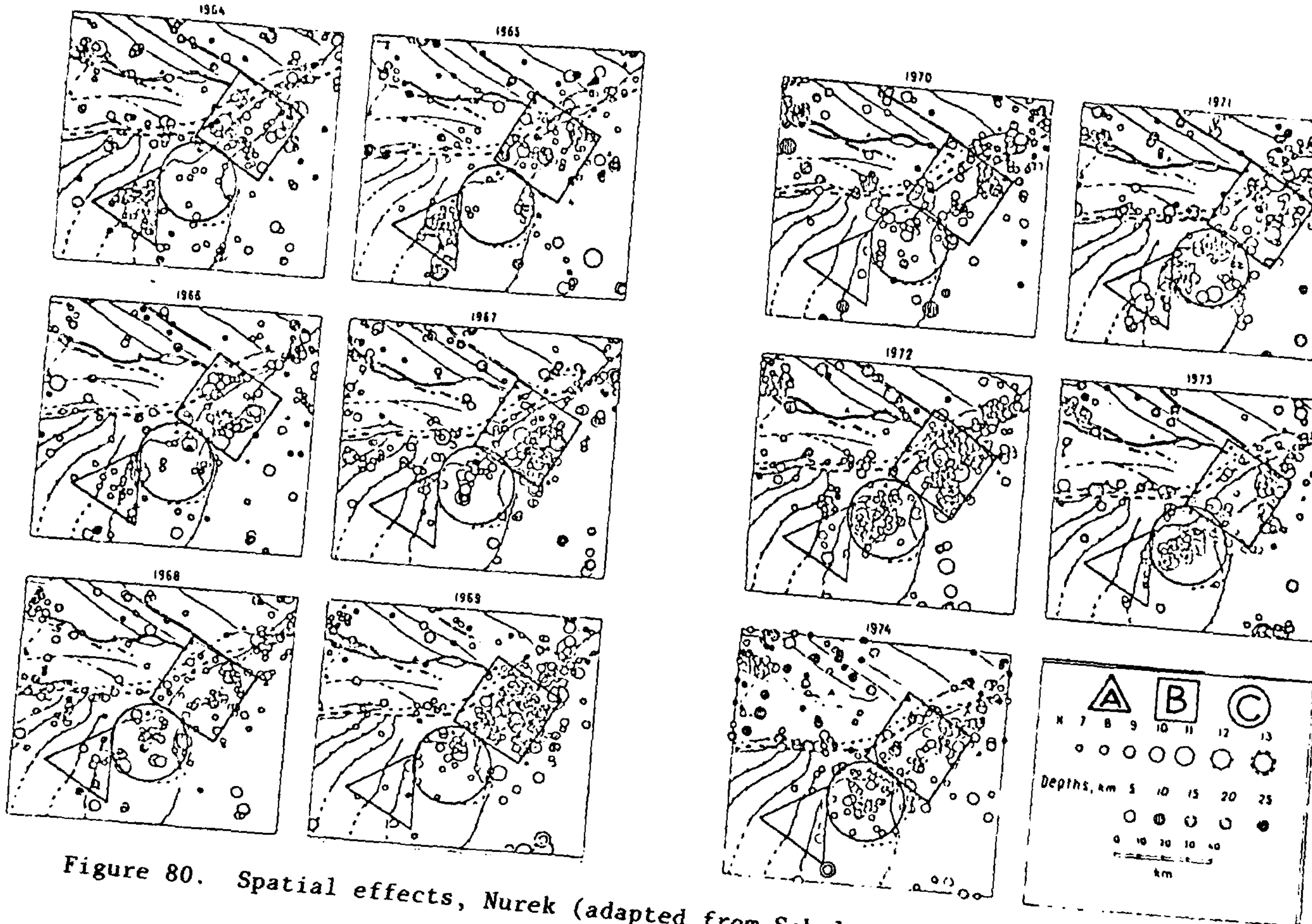


Figure 80. Spatial effects, Nurek (adapted from Soboleva and Mamadaliev (1976))

Induced Aseismicity

265. Under certain conditions a reservoir may inhibit seismicity. This is particularly true if there is not fluid communication and only load effects are felt. In environments where the minor or intermediate principal stress is vertical the reservoir may promote stability. Cases of this type rarely receive attention. Two candidates for induced aseismicity are the Anderson Reservoir in California and Tsengwen Reservoir in Taiwan. A brief look at these cases follows.

Anderson Reservoir, Calif.

266. The Leroy Anderson Reservoir is located on the active Calaveras fault. There is a seismic gap whose location coincides with the reservoir. A magnitude 4.3 event did occur within the gap on 7 October 1973. An event of this type on the Calaveras fault is typically immediately followed by hundreds of aftershocks but in this case only one event, magnitude 3.4, occurred 50 hr after the larger shock. Bufe (1975) suggests that the increased pore pressure near the reservoir has promoted stable slide or creep instead of stick-slip behavior. This fault is a strike-slip fault. Since 1950 the reservoir area has shown a 0.5 to 0.9 cm/yr creep rate based on damage observed at Cochrane Bridge located at the reservoir.

Tsengwen Reservoir, Taiwan

267. This reservoir has a 128-m maximum depth and is located over an active thrust fault, the Chuko fault. This fault was apparently the causative fault for a magnitude 6.7 (M_s) event in 1964. The reservoir was impounded in 1973 in this highly active area. The reservoir impoundment did not produce a seismic gap but reduced the number of very shallow focus events (<2.5 km) from the number common before filling (Wu, Yeh, and Tsai 1979). Seismicity does persist at deeper focal depth and is clustered offset from the dam to the southeast. There is no evidence of deep fluid communication. Elevated fluid pressure is common to northwest Taiwan at depths greater than 3 km. It is not known whether this condition is applicable to the reservoir area.

PART V: SUBJECTIVE JUDGMENTS

Limitations of Circumstantial Evidence

268. Circumstantial evidence does not produce a deterministic outcome. The evidence must be evaluated. The evaluation may be conducted using objective standards, but the quality of the evidence will affect its evaluation. An approach to this problem is the process of statistical decisionmaking. The quality of the basic data is specified and hypothesis tests are performed. The outcome of the hypothesis test determines the decision. This process is widely used in industrial quality control and was recommended for testing for an increase in seismicity and applied to the data for Nurek. This procedure is only effective when the basic input data meet certain standards. When a deterministic decision must be reached based on circumstantial evidence that is inadequate for use in statistical decisionmaking, the decision maker must use subjective judgment. It is subjective because the evidence is weighted according to standards developed through experience. In the case studies most of the basic seismicity data were inadequate to use statistically, and the correlation evidence is not reducible to statistics because of the nature of the triggering process. The evaluation of the case studies is the subjective evaluation of circumstantial evidence.

269. The process of assessing the quality of the data, described in Parts II and III, was applied in the review of the case studies. The outcome of the evaluation of the evidence is an opinion, a subjective judgment. In dealing with actual engineering projects, decisions, not opinions, are required. In this spirit it is necessary to make a decision regarding induced seismicity for these cases. The decision is unambiguous. A case is or is not induced seismicity. The decision is derived from an opinion which may be held with various degrees of confidence. If the available data are of good quality, an opinion may be formed with a large degree of confidence. If little or no data are available, or the data are conflicting or ambiguous, no responsible

decision can be made. This situation is shown in Figure 81. If some seismic discriminant were available and included in the data, the evidence would no longer be circumstantial. A deterministic decision would be straightforward. Since only circumstantial evidence is available, an opinion will be given and the degree of confidence associated with the opinion will be indicated. Decisions will be given for those cases with better data. These opinions are summarized on Figure 82.

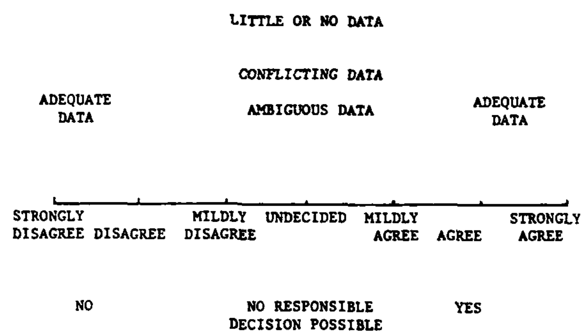
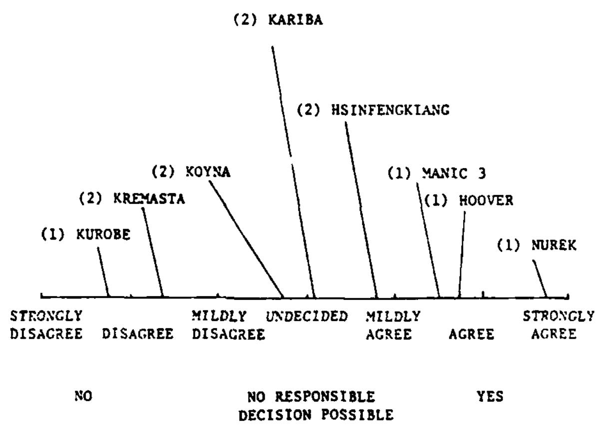


Figure 81. Opinion/decision diagram



(1) KUROBE	(2) KOYNA	(1) MANIC 3
(2) KREMASTA	(2) KARIBA	(1) HOOVER
	(2) HSINFENGKIANG	(1) NUREK

(1) LOW LEVEL MACROSEISMICITY
(2) EARTHQUAKES OF ENGINEERING INTEREST (M>5.8)

Figure 82. Opinion/decisions

Review of Cases

Hoover (postimpoundment seismicity
category I, correlation category +)

270. The Lake Mead region experienced an increase in seismicity coincident with impoundment. In the 15 years prior to impoundment there were no events ($M_L \geq 4.5$). In the 29 years after impoundment there were 12 events ($M_L \geq 4.5$). Of the 12 events, 8 occurred at times when the reservoir was reducing the stability of the region; 3 occurred when the stability of the region, in terms of reservoir effects, was increasing. For the remaining events, the stability of the area cannot be estimated.

271. Hoover Dam and Lake Mead represent cases of induced macroseismicity. The region is the site of Cenozoic volcanism which is a trait shared with Koyna. The region still possesses terrestrial heat from this volcanism as evidenced by the warm springs found in the Nevada abutment. The role of temperature gradients that may have been influenced by the reservoir is a source of uncertainty not modelled in the triggering theory. The magnitude of the influence of changing temperatures is unknown. The existence of warm or hot springs in itself is not ominous. Roosevelt Dam in Texas also encountered warm springs during construction.

272. The regional rebound, which was recorded in the geodetic survey, is difficult to interpret. Either the survey data are incorrect or substantial crustal strains have taken place at Lake Mead due to forces other than the reservoir.

Kariba (Q, Q)

273. At Kariba the data alone are inconclusive. The main burst of activity did nearly coincide with maximum loading. The lack of preimpoundment data is particularly unfortunate. The reservoir is located in a rift valley not known for its seismic activity. The eastern rift areas are better documented. The reservoir area did hold at least one active fault at Binga. Additional active faults may have been present in the eastern portion of the reservoir where the large events ($M > 5$) occurred. The significant macroseismicity took place during September

1963. This activity was centered in the deepest portions of the reservoir and may have been triggered.

Kremasta (N, Q)

274. At Kremasta there are two sets of seismic events which are unrelated. First, the event of February 6, 1966, fits into the pattern of historic seismicity of the region. The event took place well outside of the reservoir boundary at a depth which is uncertain but probably not shallower than 20 km. This event appears unrelated to impoundment. Second, there were felt events at the damsite. Enough of these occurred to cause public alarm and they persisted at least through 1973. There is no information regarding location of these events with respect to the reservoir. There is no conclusive evidence to indicate that the macro-earthquake was induced.

Koyna (I, O)

275. The diffuse nature of the seismicity at Koyna is bewildering. If there is an active fault south of the dam as indicated by Cluff (1977), the seismicity should be better aligned with that fault. The seismicity is centered on a region south (downstream) of the dam and it has increased coincident with impoundment but shows little spatial or temporal relationship to the reservoir. The focal depth ranges from 0 to about 30 km but is generally 2 to 8 km in depth. This places the bulk of the seismicity below the trap rock in a basement rock of unknown composition. The geophysical studies conclude that the basement rock is crystalline and is faulted near the continental divide and parallel to it.

276. West of the continental divide a zone of hot springs runs parallel to the divide. The springs are very hot and volcanic in origin. The relationship between the springs and the event of 10 December 1967 is unclear. Some scientists claim the springs responded to the event. This would not be unusual in cases of natural seismicity. The seismic history of the region is poorly documented. Gubin (1969) gives a summary which indicates that felt events have occurred along the coast and in the plateau area of the traps. Some researchers (Gupta and Rajguru 1971) claim that there are recent flows in the traps and that

the seismicity is a renewal of volcanic activity. The larger events at Koyna originate at focal depths below the trap rock. The events occurred in the faulted basement rock which was also the source of volcanic activity and still intense enough to power a zone of hot springs. Temperature and discharge fluctuations have taken place in the springs, which indicates that the potential for renewed volcanism is present. The seismicity, which increased in the 1960's and continues today, may represent active tectonism, renewed volcanism, or induced seismicity. Based on the locations of the events, both depth and distance downstream, the Koyna project is unrelated to the observed seismicity.

Kurobe (N, 0)

277. The macroearthquakes at Kurobe fit easily into the historical seismicity of the area. Only three events ($M \geq 3.8$) are associated with the reservoir. The two largest events occurred in August 1961 at locations which are close (<20 km) to epicenters of large ($M = 6$) historic events. The remainder of the events are microearthquakes which may have been occurring at the site prior to impoundment. This does not appear to be a case of induced seismicity.

Manic 3 (I, +)

278. The events at this reservoir consist of one event ($M_b \approx 4.1$) and over a thousand microearthquakes. The reservoir area was monitored prior to impoundment and in the 8 months prior to filling no microearthquake activity was detected in the area of the reservoir. Filling began on August 5, 1975, and events began to occur in mid-September.

279. The largest event occurred on October 23, 1975, and was felt only at the damsite and nearby switching station. Filling was completed in December 1975 and the reservoir was held at a nearly constant level. The earthquake activity faded out substantially by April 1976. In May the microearthquakes increased without reservoir change. Low level activity persisted for 2 years after filling. The activity could be a coincidence but appears to have been triggered by filling.

Hsinfengkiang (I, +)

280. The reservoir area experienced an increase in felt events after impoundment. The largest event occurred shortly after the

reservoir reached maximum load. The major source of uncertainty in this case is that the one large event dominates the seismicity near the reservoir. If that event were unrelated to the reservoir, the increase in felt events prior to the main event could be interpreted as foreshocks. The persistence of aftershocks near the epicenter is not unusual considering the size ($M_s = 6.1$) of the main shock. The evidence that suggests the event's relationship to the reservoir is its proximity and the timing. The region was referred to by the Chinese as "unstable," and it is possible the event could be unrelated to the reservoir.

Nurek (I, +)

281. This case is the only one where detailed preimpoundment seismicity studies were conducted, which permitted changes in seismicity to be recognized. The data were complete enough to justify statistical treatment. The seismicity information was sufficiently detailed for detection of a change in the spatial distribution of events during changes in the water level.

282. The seismicity at Nurek appeared to have been triggered and the impoundment seemed to modify the behavior of certain faults by moving the location of activity along a fault in response to filling.

Conclusions

283. The following conclusions are drawn from the evidence presented in support of induced seismicity:

a. All available evidence of induced seismicity is circumstantial. The evidence contains no factors unique to induced seismicity. Changes in seismicity over time are the rule rather than the exception. No seismic discriminant is available to positively indentify induced events.

b. Accurate catalog information must be available to permit detection of changes in seismicity. Unless normal seismic behavior can be identified, induced seismic behavior cannot be recognized. The characterization of seismicity is usually constituted by either a magnitude-frequency or a time-frequency relationship. Both of these measures are derived from catalog information. The accuracy of epicenters and hypocenters must be known.

c. Stress distribution based on a homogeneous elastic crustal model is not representative of field conditions except in unusually simple geologic conditions. Comparison of predicted deflections with measured deflections at reservoir sites shows that homogeneous elastic models fail to accurately predict the measured deflection. Since stress is proportional to strain in linear elastic models, the predicted stress will also be in error.

d. Statistical techniques can be used to determine significant change in seismicity coincident with impoundment. Simple distribution-free tests are available to evaluate the change in seismicity before and after impoundment.

e. Correlation evidence of induced seismicity cannot be properly evaluated using statistical techniques. The statistical measures require that the data be independent pairs of a reservoir and a seismic parameter. The reservoir parameter (water level or load) will assume some given value during both rising and falling reservoir level. The response of the crust as measured by the seismic parameter may be different during rising and falling lake levels but the correlation statistic cannot account for this.

f. Evidence based on b values is meaningless in evaluating induced seismicity. The b value may be time varying and the value of this parameter is sensitive to data accuracy, magnitude bias, and the method used to calculate the parameter. All b value trends attributed to induced seismicity can be found in natural seismicity as well.

g. A review of eight cases of induced macroseismicity confirms three cases (Hoover, Manic 3, and Nurek), rejects two cases (Kurobe and Kremasta), and leaves three cases undecided (Kariba, Koyna, and Hsinfengkiang).

h. There is no unequivocal case in which a damaging earthquake ($M > 6$) has been triggered by reservoir impoundment.

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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Meade, Ronald B.
State-of-the-art for assessing earthquake hazards in the United States : Report 19 : The evidence for reservoir-induced macroearthquakes / by Ronald B. Meade (Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, 1982.
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